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MEASUREMENT OF OCEAN SURFACE CURRENTS

USING A SHIP TOWED LOG

by

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May 1980

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Department of Ocean Engineering

MEASUREMENT OF OCEAN SURFACE CURRENTS USING A SHIP TOWED LOG

ABSTRACT

A ship towed log for use on ships-of-opportunity to measure ocean surface currents was built and tested over the past two years. The technique used is one of the oldest known to navigators. The ship's dead reckoned position is calculated from the speed and heading as measured by the towed log. This is then compared to the ship's true position as obtained from a reference navigation system (Loran, satellites, etc.) and the difference is attributed to the currents encountered by the ship. The system was used on six sea cruises and was successfully towed over 11,000 miles. While it is not capable of making high precision current measurements as would be obtained from moored current meters, it can distinguish features on the order of 20 to 30 cm/sec. over a large horizontal scale in the upper ocean.

ACKNOWLEDGEMENTS

This project would not have been possible without the guidance of Mr. Douglas Webb of the Woods Hole Oceanographic Institution and Drs. John Gould and Brian McCartney of the Institute of Oceanographic Sciences, Surrey, England. I also wish to thank Dr. Mark Carson and Roger Edge of I.O.S. for the fine work in designing and constructing the fish body. This work was supported by the Office of Naval Research under grant N00014-79-C 0071; NR 083-004.

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INTRODUCTION

The development of a ship towed log for measurement of ocean surface currents was begun as a joint development project between the Institute of Oceanographic Sciences (IOS), Wormley, England, and the Woods Hole Oceanographic Institution (WHOI) in the fall of 1977. Initial construction of the electronics was done at WHOI under the direction of Mr. Douglas Webb with final system integration into the fish body done in England. Dr. John Gould of IOS provided the primary scientific direction. To date, the towed log has been used in six cruises and this paper is intended to summarize the design and performance of the system to this time.

MEASUREMENT TECHNIQUE

The measurement technique employed is one of the oldest known to navigators. The ship's motion through the water is measured by means of a speed and heading sensor in the towed log and from this the ship's dead reckoned position is calculated. This dead reckoned position is then compared to the ship's true position as obtained from a reference navigation system such as a satellite navigator, Loran, etc. If the ship's speed and heading have been measured exactly, and the ship has encountered no currents, the two positions will coincide. However, if the water through which the ship passed is moving, there will be a displacement of the dead reckoned position which is equal to the average current times the time difference between two reference navigation positions.

From this it is obvious that the precision with which ocean surface currents can be determined is limited by the accuracy with which the ship's speed and heading through the water and the reference navigation positions can be measured.

It is essential that total ship motion relative to the water be determined and this has limited the use of the technique. Most ships incorporate only a longitudinal speed sensor and it is assumed that the athwartship motion is negligible. Unfortunately, if the ship encounters crosswinds, the assumption is invalid and major errors can be introduced in calculating the surface currents. Therefore, from hull mounted sensors a two axis speed log is essential.

Two component electromagnetic logs have been used on RRS DISCOVERY and RRS SHACKLETON for many years, and surface current measurements have yielded some very useful data (1,2,3,4).

There are several disadvantages to a hull mounted log however. In general the calibration of the speed sensor is greatly modified by flow characteristics of the water around the hull and a calibration must be made after the sensor has been installed on the ship. While this is relatively straightforward for the longitudinal component of the speed, it is a somewhat tedious and difficult procedure for the athwartship component. Typically the ship must be allowed to drift near a surface float while the relative positions of the two are constantly monitored. In addition, it is very difficult to get a calibration curve over a range of athwartship speeds.

Should it be required to move the system to a different ship, the sensor must be mounted in the hull which may require dry docking it, and the calibration redone.

Thus while the hull mounted system has been used successfully, it is not a highly portable system and its use is restricted to research ships where it is possible to invest the time and money to make it work.

SYSTEM DESCRIPTION

The primary goal in designing the new system was to make it portable enough to be used from a large number of ships, specifically any ship of opportunity. In order to avoid the problems of the hull mounted system, it was obvious that the sensors would have to be deployed at a distance from the hull of the ship. This naturally led to a towed fish configuration with data logging and/or processing done aboard the ship.

By physically separating the speed sensor from the ship, however, it is no longer possible to get heading information from the ship's gyro compass since the movement of the ship and that of the fish will differ. Therefore, the fish must carry both speed and heading sensors.

A block diagram of the overall system is shown in Figure 1. In addition to the speed and heading sensors, several measurements for evaluating the fish dynamics have been incorporated. These include pendulous roll and pitch sensors, a pressure transducer for determining its depth, and several calibration voltages. A temperature sensor has also been included as an aid in relating the surface currents to the ocean structure.

The data logging electronics follows conventional practice for this type of system. The twelve channels of data are sent to a multiplexer and each are converted to a parallel digital word using a 12 bit analog-to-digital converter. The converter is an Analog Devices Model 7550 monolithic integrated circuit. Although the conversion rates are rather slow, about 40 milliseconds, the unit has very low drift errors and requires very little power to operate. The 12 bits from the A-D converter are then broken up into four three bit words which are coded as ASCII digits 0 through 7. These are then converted into a serial teletype code, frequency shift key modulated with 600 Hz and 1200 Hz square waves, amplified and transmitted up the tow cable. Each of the twelve measurements is digitized and transmitted once per second followed by the ASCII characters for

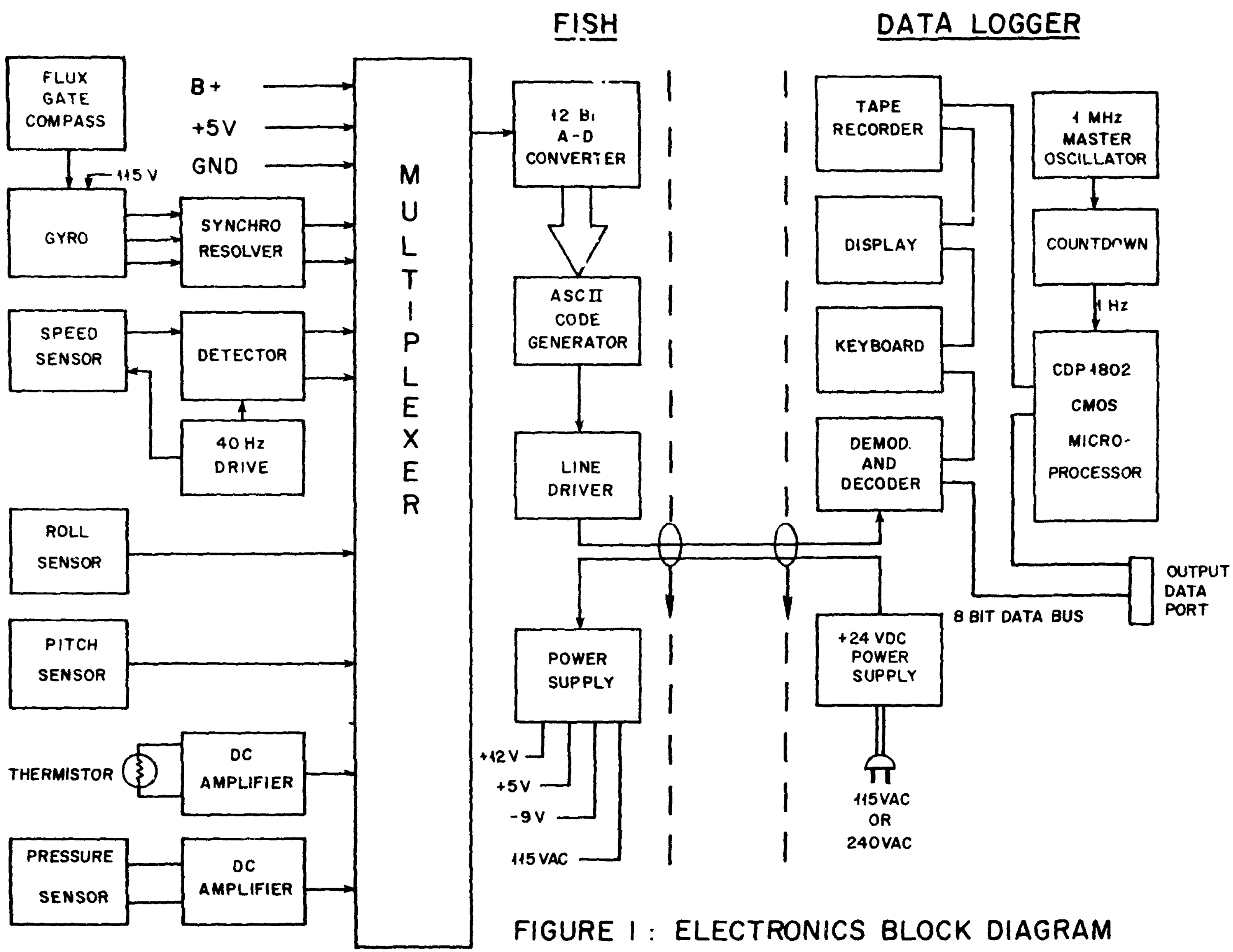


FIGURE 1 : ELECTRONICS BLOCK DIAGRAM

carriage-return and line-feed which signify the end of the one second data frame.

Power for the fish electronics is +24 VDC at 1 ampere and is transmitted from the ship down the tow cable.

The fish is towed from the ship using a single cable which serves both as a load member and contains the necessary electrical conductors to get the power to the fish and the data signals back to the ship.

A data logger is mounted on the ship and records data from the fish on magnetic tape. Its main components include the tape recorder, master clock, display, and power supplies for both the fish and the data logger. Data coming up the cable is demodulated, formatted, and then stored in a temporary memory until ten seconds worth has been accumulated. It is then combined with the time from the precision clock and stored on the tape. A digital display is provided which can be manually selected to display the time from the clock or any one of the data parameters from the fish.

An RCA 1802 microprocessor was used as the controller for all functions in the logger. Its flexibility and capabilities are impressive, and by using it the hardware complexity was greatly reduced with a corresponding increase in reliability. No electronic hardware failures have been encountered to date.

The tape recorder is manufactured by Data Electronics Inc., and uses a DC 300 tape cartridge. This cartridge contains 300 feet of .25" wide magnetic tape and has a capacity of 24×10^6 bits of data. With the present sampling rates, a cartridge is filled about every 24 hours which is very convenient for the operator. Processing of the data is done on a shore-based computer using the data logger as the tape reader to get the data into the computer.

SENSORS

IOS has had a great deal of experience in both building and using electromagnetic speed sensors and it was decided that this type of sensor would be used in order to take advantage of this .

The sensor itself consists of a coil of wire contained inside an 11 centimeter diameter epoxy discus with four electrodes imbedded every 90° around the bottom face. The coil is driven with an AC current which produces a magnetic field in the water normal to the bottom face of the sensor. When the water flows by the face, an electric field is generated normal to the flow equal to the cross product of the velocity and magnetic field ($\overline{E} = \overline{V} \times \overline{B}$). The electric field is detected as a voltage between the electrodes, and by having two sets of electrodes oriented at right angles to each other, the two components of flow, longitudinal and athwartship, can be determined.

The signal from the electrodes is very small, typically 100 μV per meter per second, so it is amplified with a high impedance, high gain, differential AC amplifier followed by a synchronous detector to provide a DC voltage output that is proportional to the water speed. The processes at the sensor face involving the AC magnetic field, inhomogenities in the water, water motion and electrode materials are very complex, but by using a square wave coil drive and allowing the transients to die out before sampling, most of the nonlinearities and errors have been eliminated.

Flow tests on this sensor have shown that speed accuracies of 1% are attainable with noise floors on the order of 5 cm/sec. Rotations of the flow in the plane of the sensor give good response with deviations of approximately 1% from the ideal. Changes in the angle of attack cause more serious errors, but since it is expected that the fish will be a stream follower, both coplanar and angle-of-attack deviations of the flow should be very small. Frequency response can be tailored to the application by varying the high frequency roll-off of the synchronous detector.

IOS has used this sensor for many years on their research ships and it has proven to be very rugged, reliable, and highly accurate.

The heading sensor consists of a gyroscope slaved to a flux gate compass. It is manufactured by the Aircraft Instrument Manufacturing Co. and is intended for use as a compass system for light aircraft. It has several advantages over a simple magnetic compass. Since the earth has a relatively large magnetic field component normal to the surface except at the magnetic equator, it is necessary to design any compass so that it senses the tangential field and is not affected by changes in the strength of the normal component. This is usually done by mounting the compass in a gimbal so that it is always oriented to the local horizontal. Unfortunately, if the local horizontal should be modified, such as when a banked turn is being made, the compass will sense some of the normal magnetic field and sizeable errors in direction occur. Secondly, a magnetic compass is very noisy in that movement of the fish body which causes the gimbal to swing or local disturbances which cause temporary distortion of the local fields will be directly seen in the heading.

The slaved gyro gets around these problems to a large extent. Basically the instrument consists of a gyroscope which is slowly precessed (1° per minute) to align with magnetic north as measured by a flux gate compass. Thus the heading output has the short-term stability of a gyroscope with its immunity to the effects of fish motion while the long-term drift errors of the gyroscope are corrected by the flux gate compass.

The heading is obtained from a synchronous repeater which is geared

MEASUREMENT	SENSOR TYPE	RANGE	ACCURACY	RESOLUTION	SAMPLING RATE
SPEED	2 AXIS ELECTROMAGNETIC 11 CM DIAMETER DISCUS HEAD SUPPLIED BY IOS	LONGITUDINAL -5 TO +15 M/SEC TRANSVERSE ±5 M/SEC	1% OF READING	.5 CM/SEC	1 SEC
HEADING	SLAVED GYROSCOPE AIM MODEL 400 CEL	0-360°	±1°	.1°	1 SEC
ROLL & PITCH	PENDULUM POTENTIOMETER HUMPHREY MODEL CP-17	± 45°	±1°	.02°	1 SEC
PRESSURE	STRAIN GAGE PAINE INSTRUMENTS MODEL 211	0-300 PSI	±1.5 PSI	.1 PSI	1 SEC
TEMPERATURE	THERMISTOR YSI MODEL 44032	0-30°C	.01°C	.01°C	10 SEC

TABLE I: TOWED LOG MEASUREMENT SUMMARY

WHOI-DWG-LRM-78

to the gyro. The repeater is driven with a 400 Hz sine wave which then generates a three phase signal that unambiguously represents the position of the gyro. These three signals are then sent to a resolver which converts them to the equivalent sine and cosine components of heading.

The gyro motor requires 115 VAC, 400 Hz and runs at 23500 RPM. It is gimballed and can operate at roll and pitch angles of up to ±80 degrees from the horizontal.

The remaining sensors include pendulum potentiometers for roll and pitch, a 0-300 PSI pressure transducer, and a 0-30°C thermistor for sea water temperature. Table 1 summarizes the sensors and their characteristics.

In addition to the sensors, the electronics samples the power supply voltage in the fish, the 5V power supply level, the zero volt ground, and the slaving voltage which is proportional to the difference in magnetic north as measured by the gyro and the flux gate compass. This latter measurement is used only as an aid in calibrating the heading sensor.

TOW CABLE

The tow cable is a .322" diameter, double armored well logging cable. Its characteristics are summarized in Table 2. The primary considerations in its choice were sufficient density to maintain depth at the projected operating speeds, reasonably good torque balancing under tension, adequate strength and fatigue immunity, a sufficient number of electrical conductors, reasonable price, and availability.

Cable Diameter	.322 inches
Weight in Water	2.2 N/meter
Breaking Strength	8000 pounds
Armor	Mild steel, 2 layers
Electrical Conductors	7- #22 AWG
Electrical Resistance	11.1 OHM per 1000 feet

Table 2: Tow Cable Characteristics

HYDRODYNAMIC CONSIDERATIONS (5)

In designing the fish and selecting a tow cable, it was important that the resulting combination provide a relatively stable platform over the range of speeds of interest yet be a relatively rugged, easily deployed system. Prior to the towed log, a successful design for a towed side scan sonar, GLORIA II, was done at IOS. A large amount of experience accumulated in that project was applied to the design of the towed log.

The design constraints for the system can be defined very simply. It was decided that the initial design should operate for ship speeds of up to 18 knots and should be simple enough for one or two people to deploy and retrieve without the need for specialized deck handling equipment. Since the electronics includes a magnetic compass, it is necessary to tow it sufficiently far aft to eliminate magnetic field disturbances due to the ship's hull which would introduce heading errors into the compass. Similarly, the fish must be towed deep enough to avoid the disturbed water in the ship's wake which could adversely affect the speed sensor. Finally, the fish must be stable enough so that the various sensors, primarily the gimballed gyro and flux gate compass, can operate properly.

The problem can be divided into two parts by first considering the tow cable with a body of unspecific characteristics, and then looking at the body in detail with regards to stability and towing characteristics.

Bullard and Mason (6) have shown that the disturbance to the earth's magnetic field is directly proportional to ship length, and that at four lengths it is negligible (approximate 0.2° error in heading) so that for a ship of 75 meters length, it should be towed at least 300 meters aft. Permanent magnetization of the hull, while varying from ship to ship, is also negligible at this distance.

Similarly, the growth of the ship's wake and its penetration into the upper water levels can be estimated based on the work of Schlichting (7). Extending slightly his expression for the wake of a submerged asixymmetric body gives the following values of wake depth as a function of distance aft for a ship with a 5 meter draft moving at 9 m/sec.

Distance Aft	Wake Depth
50 m	12 m
100	14
200	16
300	18

Therefore it is necessary that the fish tow at least 18 meters below the surface at 18 knots.

This depth can be achieved with the cable alone so that no depressors or weights should be necessary on the fish. With a cable of 8 mm diameter and weight in water of 2.2 N/meter, the critical angle (the angle at which the cable tows by itself) is 4° at 18 knots which gives a fish depth of 21 meters at 300 meters aft. Using the methods derived by Pode (8) and accounting for the drag of a neutrally buoyant body gives the expected depths as a function of ship speed listed below.

Speed M/S	ϕc Deg.	D N	S M	Y M	$\overline{Y}$ M
2	18.8	50	16	3.1	95
3	12.6	113	20	2.6	64
4	9.4	201	23	2.3	47
5	7.5	314	26	2.1	38
6	6.3	453	28	2.0	32
9	4.2	1018	40	1.0	20

where ϕc = cable critical angle

D = drag of neutrally buoyant body of diameter = 25 cm.

S = scope of cable affected by body

Y = depth due to scope S

$\overline{Y} = Y + (300 - S) \sin \phi c$

Since the critical angle is very small over the whole range of speeds, a simple nose towed vehicle can be used. While it appears that towing a body from the nose should guarantee its yaw stability, the center of pressure may actually lie ahead of the tow point in the case of a slender streamlined body. This can be corrected, however, by the addition of a tail of sufficient area.

A picture of the fish is shown in Figure 2. Its basic size is determined by the size of the electronics package which consists of a 6.5 inch diameter aluminum tube with a cantilevered arm off the aft end to physically separate the flux gate compass from the rest of the electronic circuitry. The electronics housing is mounted in the lower part of the fish with the upper voids filled with plasticell foam to provide roll resistance. The roll performance is determined by the applied cable torque, the body righting moment, and the roll damping. For a body drag of 1000 N at 18 knots, the cable selected induces a torque of 1.4 N which must be balanced by the body static righting moment. To keep the roll angle small, say 5°, requires a righting moment of 15 NM/radian. Roll damping was maximized with the use of a ring with cruciform tail.

Pitch response is related to that of yaw. While the body is basically a streamline follower, there may be residual errors due to imperfect static balancing. Severe pitching would adversely affect the response of the speed sensor either through angle-of-attack changes in its response, or through wake shedding from the fish body. The latter can be minimized by moving the sensor sufficiently far from the boundary layer and positioning it near the nose.

The resulting fish is approximately 25 cm. in diameter, 155 cm. long, and weighs 128 pounds in air after ballasting.

FIGURE 2: FISH BODY

FIELD TESTS

Fabrication of the system was completed in July 1978 and sea trials were begun in August 1978 and have continued through January 1980. The system was first deployed from RRS SHACKLETON during the JASIN exercises, and immediately following this it was put on the ATLANTIS II and towed from the JASIN area back to Woods Hole. Most of the data on towing performance were taken on the SHACKLETON cruise as there was ample time to work at various cable lengths, ship speeds and under various ship maneuvers.

Additional sea tests then included the R/V GYRE NORPAX shuttle run from Hawaii to Tahiti in the spring of 1979; the October 1979 ATLANTIS II cruise in support of Dr. H. Stommel's Beta Spiral work in the mid-Atlantic; a December 1979 cruise aboard the R/V OCEANUS in the Gulf Stream; and finally, on the R/V THOMAS WASHINGTON during the January 1980 Pacific Fronts Experiment.

Installation, deployment, operation, and recovery of the system was very simple on all ships. During the SHACKLETON, OCEANUS, and the first ATLANTIS II cruises the fish was deployed and towed from the aft end A-frame, and from a side A-frame on all the other cruises. Deploying the fish from the side makes recovery much easier and less risky since the fish always swings when it is being brought aboard and it is less likely to hit the ship. With one exception, the cruises were all very successful and the system was deployed, towed, and recovered under sea conditions ranging from flat calm to sea state 6. The electronics in the data logger and the fish have proven to be very reliable and have never experienced any malfunction under normal operating conditions except for some interference from radio transmissions on SHACKLETON. This problem was subsequently solved with a simple addition of extra filtering on the power lines and data line from the fish.

While the gyro in the fish is relatively fragile, it has apparently not been affected by the normal abuse the fish takes during deployment and recovery. However, the electromagnetic speed sensor which protrudes from the fish is very susceptible to damage and was broken off during a deployment from the THOMAS WASHINGTON. A guard which retracts after the ship get underway is one solution to this problem, but a better one perhaps is to install an acoustic Doppler backscatter sensor. Presently, research ship-of opportunity operation presents no problems, but deployment and recovery from merchant ships would generally be very difficult.

TOWING PERFORMANCE

Table 3 summarizes the towing depth of the fish as function of cable scope and ship speed. The values for cable scope are nominal values (they should be accurate to ±3 meters) and are measured from the sheave on the A-frame. To intercompare the measured and calculated depths, this length must be modified to include only that portion of the cable in the water. However, even allowing for reasonable corrections, the comparison is disappointing. Similarly, calculations of drag coefficients or cable weights necessary to realize these results give implausible values. A post calibration of the pressure sensor following the cruise gave no indication of any problems either with the sensor or the associated electronic circuitry, so there is no reason to believe the depths are in error. This is a bit puzzling since similar calculations for GLORIA II gave a much better fit.

Cable Scope Meters	Ship Speed M/sec.	Depth Meters	Calculated Meters
200	2.65	32.9	46.5
	4.11	20.9	30.5
240	4.01	26.3	37.7
300	2.25	55.5	84.8
	3.92	34.3	48.9
	5.00	28.4	38.5

Table 3: Fish Depth vs. Ship Speed and Cable Scope

A plot of the short-term pitch performance is shown in Figure 3a along with its associated power spectrum in Figure 3b. The power spectrum is calculated by taking the Fourier transform of the time domain data and then multiplying it by its own complex conjugate. This technique is a good way to look for signals that may be buried in noise. It can be seen in the power spectrum that there is a slight peak in the range 0.2 to 0.25 Hz which may be due to ship heave being coupled via the cable. Although it is difficult to see, plot 3a also shows that the fish tows in a slightly nose up position, about 1.8 degrees. This is acceptable as the angle-of-attack errors in the speed sensor are not significant for these angles.

Similar plots for roll are shown in Figures 4a and 4b. The magnitude of the roll angles are a little disappointing, but are not totally unexpected. The average angle is about 9.3 degrees and is a function of the cable torque due to the towing tension and the righting moment of the fish. The righting moment was not measured precisely so it is not possible to compare the measured roll with the calculated value. In addition, it is possible that the cable may have been deployed with a residual torque which would add to that induced by the tension. The power spectrum of the roll shows no clearly defined frequencies which indicates there is little effect

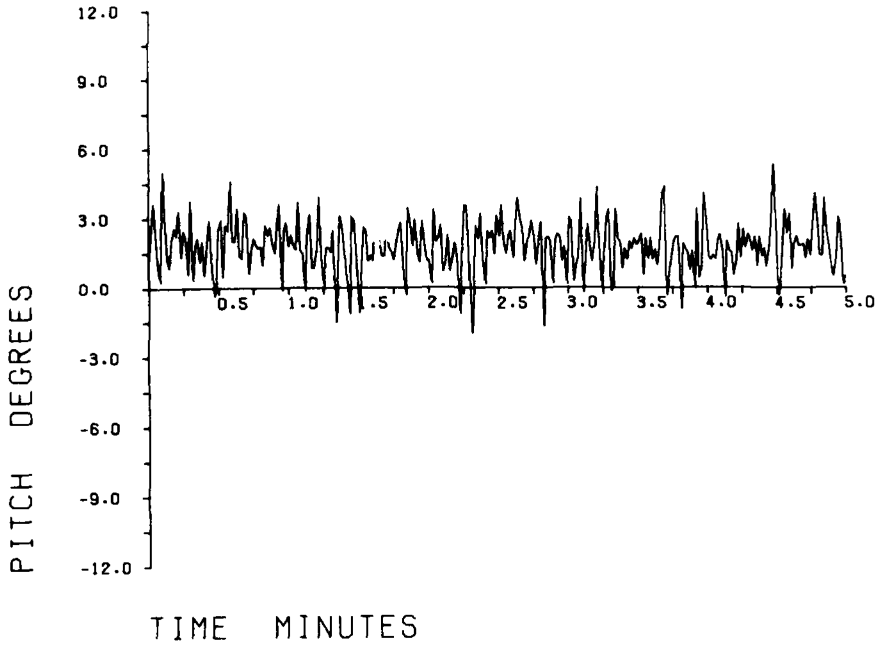


FIGURE 3a: FISH PITCH RESPONSE

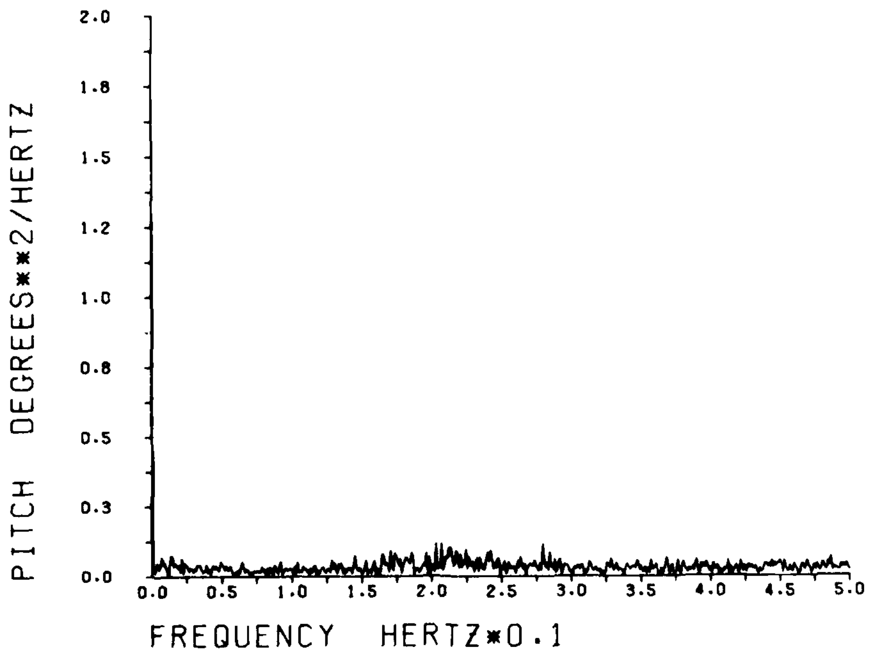


FIGURE 3b: PITCH POWER SPECTRUM

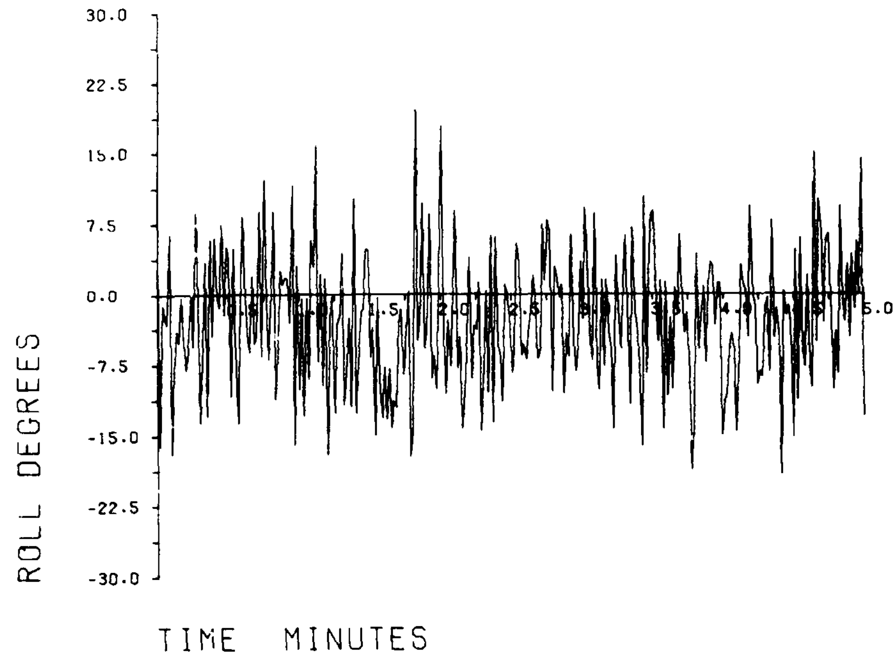


FIGURE 4a: FISH ROLL RESPONSE

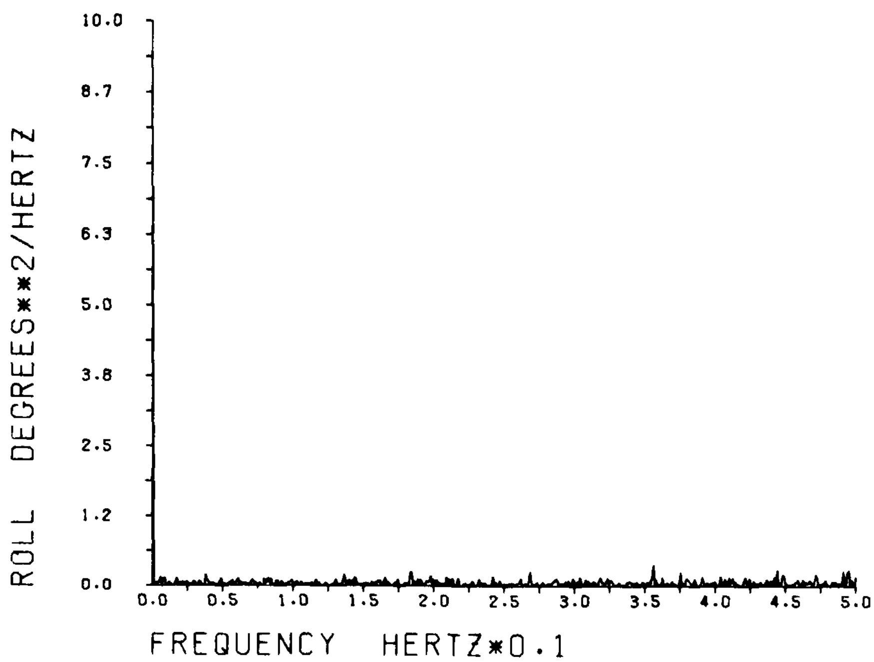


FIGURE 4b: ROLL POWER SPECTRUM

due to ship motion. It is possible that the wake of the ship extends deeper than predicted and that it is being buffeted by turbulence in the water.

The short-term yaw response is shown in the plot of heading in Figure 5. Peak-to-peak variations of about 1.5 degrees are seen which are probably reasonable based on the roll and pitch performance. In any event, there is no evidence of large amplitude oscillation as predicted and usually seen in the free end of a simple towed cable. In towing the fish, no drogues or tails were attached as stabilizing aids and it appears that none are necessary. The pitch, roll and yaw plots were made from data sets taken in the same time interval so they are all subject to the same conditions. Cable scope was 240 meters and ship speed was 5 meters/second.

Long-term plots of ship speed, tow depth, roll and pitch were made and are shown in Figures 6a through 6d. The drastic changes in the roll and pitch are not understood, but it is possible that they can be attributed to some sort of electrical problems in the sensor or digitizing circuitry. However, the other plots appear normal during these same periods and it is possible that the fish rolled over completely, but this would not explain all the transients seen in the pitch axis.

SPEED AND HEADING SENSORS

In calculating the ocean surface currents the two critical parameters measured by the system are speed and heading. These two measurements directly affect the determination of the dead reckoned position and in conjunction with the reference navigation positions directly determine the accuracy of the calculation of currents. Therefore, it is essential that they function as accurately as possible.

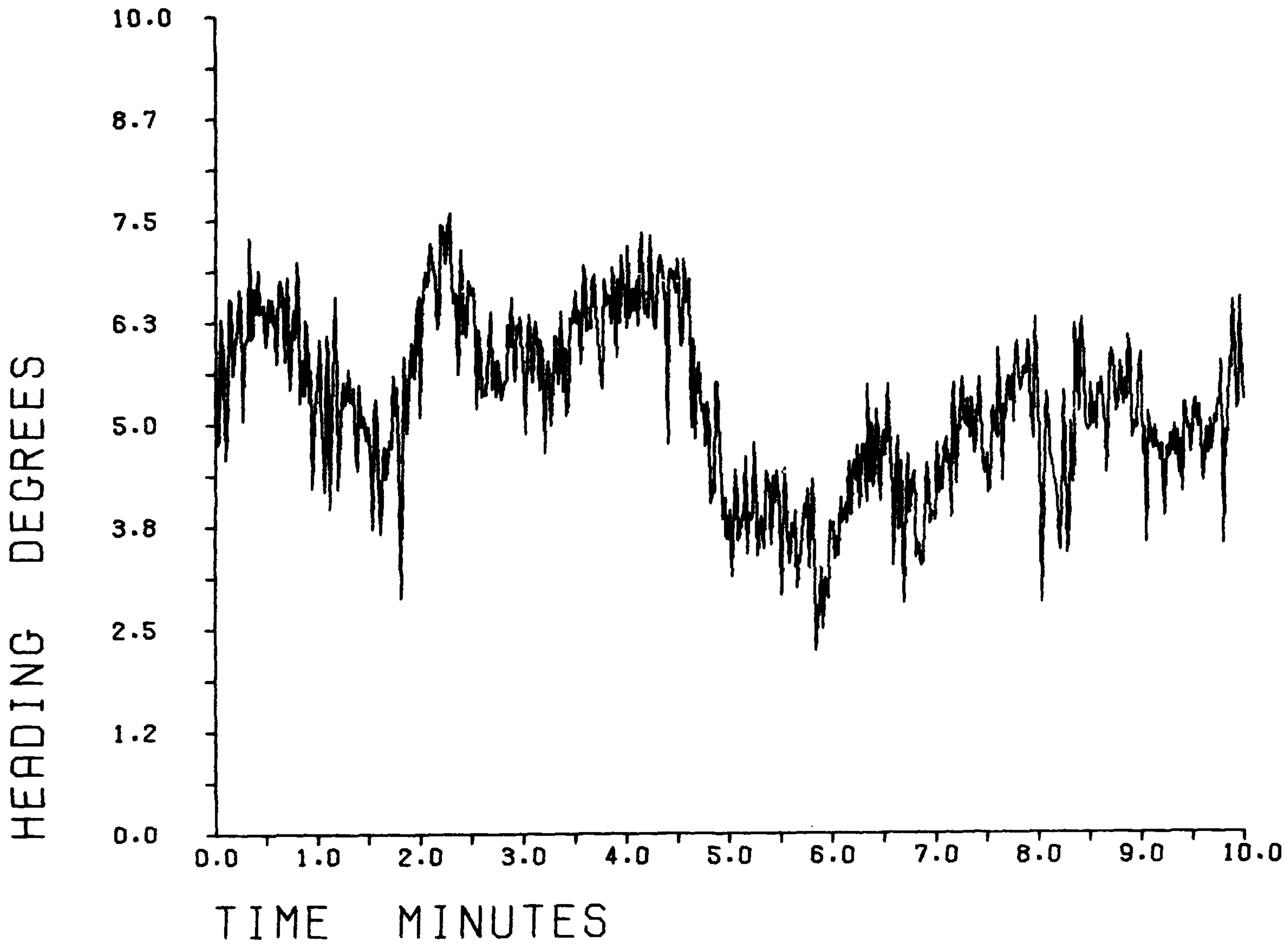


FIGURE 5: FISH YAW RESPONSE

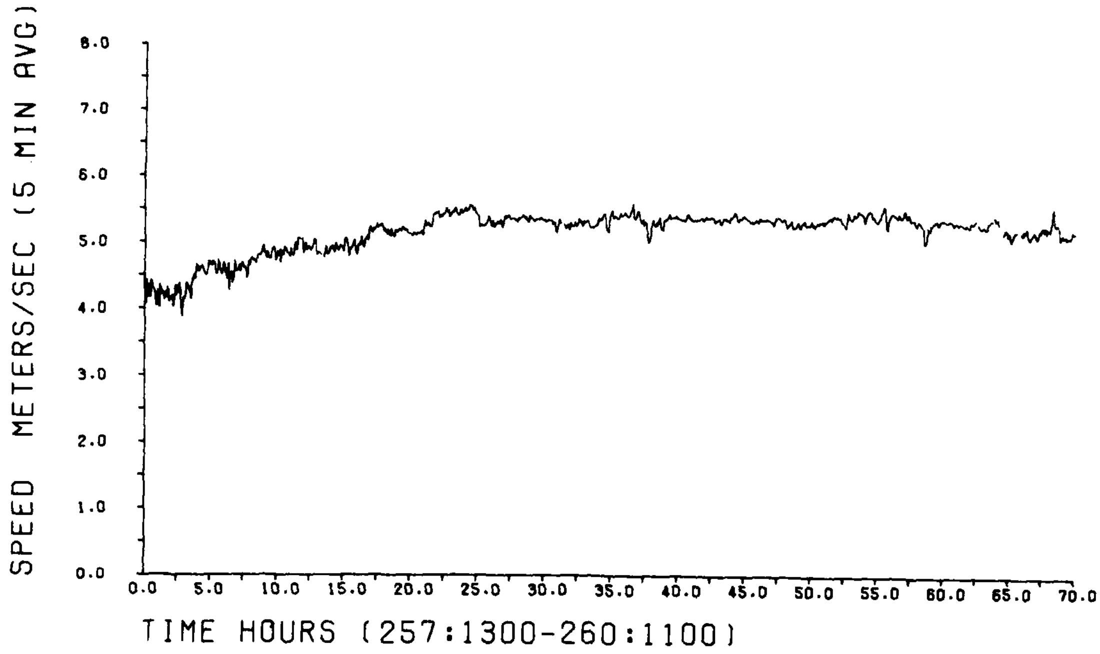


FIGURE 6a: LONG TERM SPEED

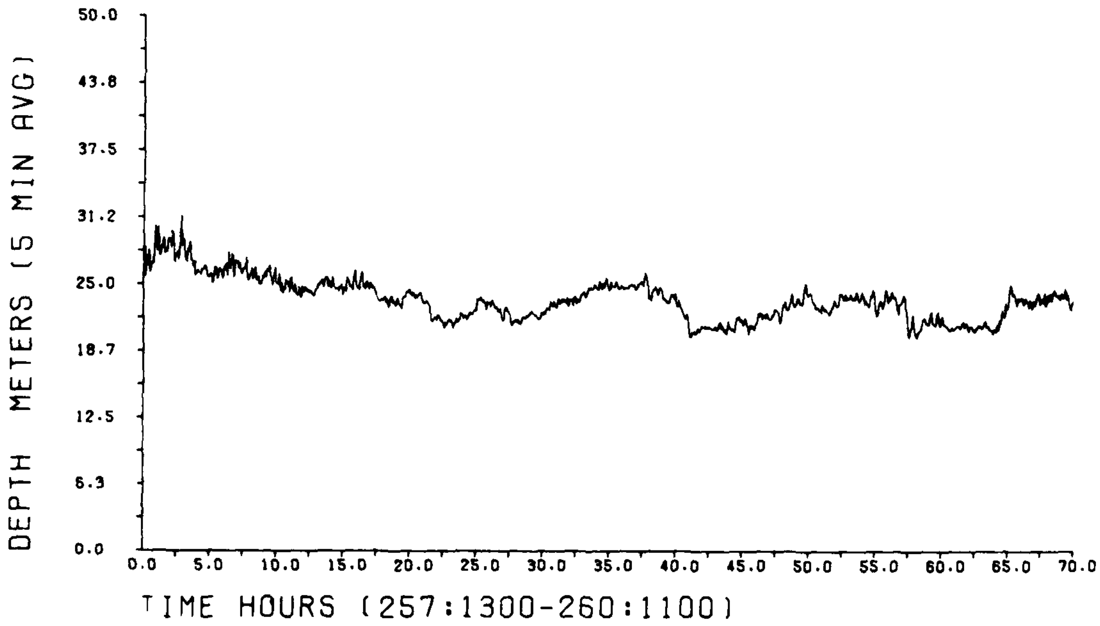


FIGURE 6b: FISH TOWING DEPTH

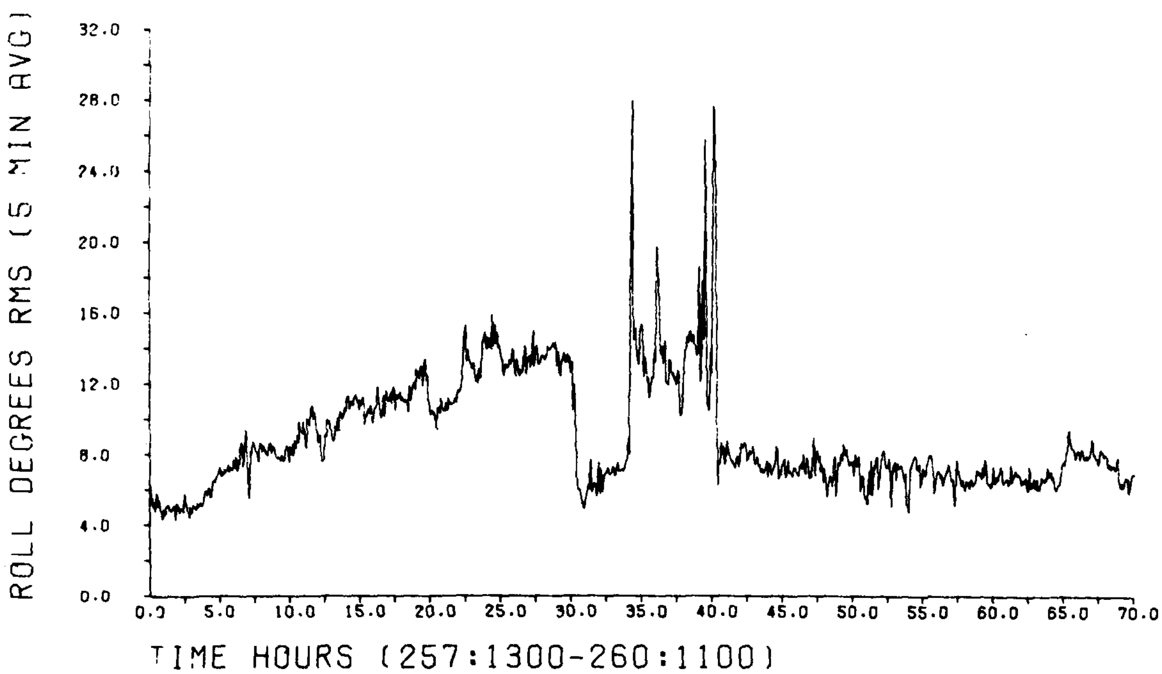


FIGURE 6c: LONG TERM ROLL

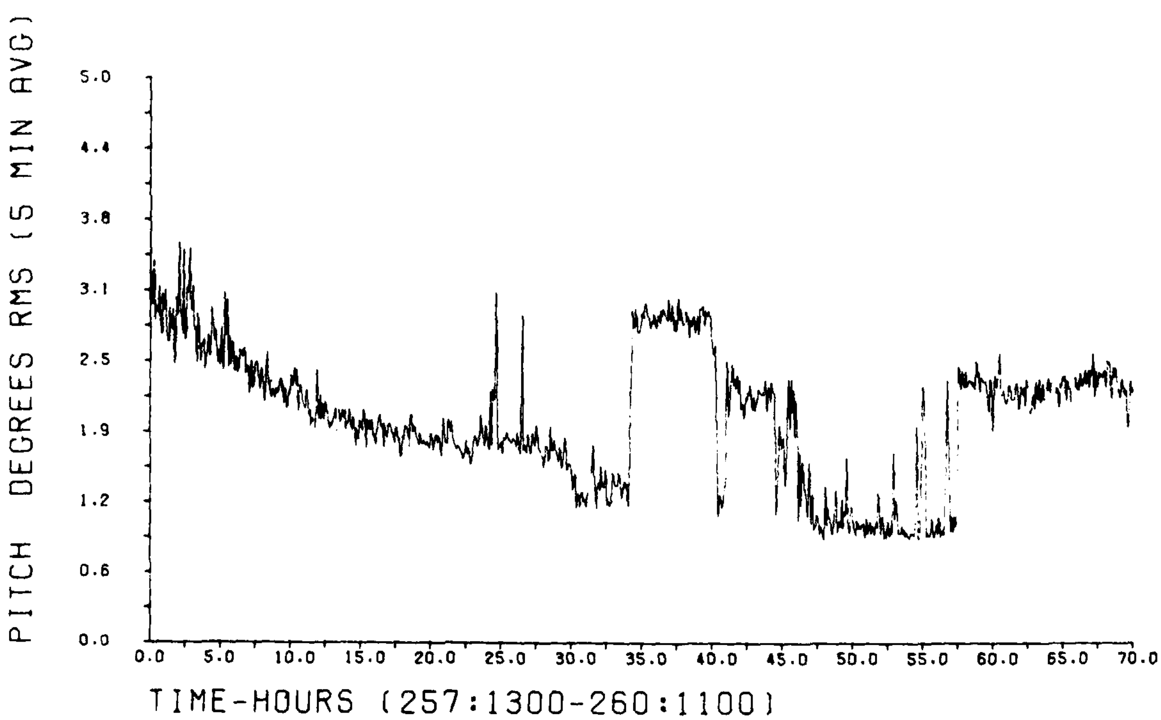


FIGURE 6d: LONG TERM PITCH

Calibration of the speed sensor was done both in England in the IOS tow tank, and in Woods Hole at the M.I.T. tow tank. The fish was assembled, mounted to the carriage and towed at various speeds to get the calibration curve. Maximum speed at the IOS facility was 200 cm/sec and 290 cm/sec at M.I.T. Outputs for higher speeds were then estimated by extrapolation.

Measurement of the cross axis speed sensor channel sensitivity was complicated by the narrow channel of the tow tanks and the resulting turbulence and wildly varying outputs, so there was probably considerable error in the result. Therefore it has not been used in determining the speed, and has been used only as a qualitative check against excessive cross axis fish motion.

The heading sensor was calibrated prior to every cruise. Typically, the gyro exhibits near perfect heading linearity as the sensor is rotated through a full circle, but due to the nonlinear response of the flux gate compass, it is then precessed slightly out of line. To generate the true headings, a correction must be added to the raw heading information to account for these errors. Fortunately, the corrections are small for most headings and are easily measured.

It would have been interesting to compare the compass calibrations done in England to those done in Woods Hole to see if the different vertical component of the earth's magnetic field at the two sites affected the flux gate compass significantly. The alignment carriage in England, however, was not capable of high precision alignments so it was not possible to make a meaningful comparison. Time was available in Woods Hole to build a good rotating table, and by using a surveyor's transit it was possible to measure heading to within ±.2 degrees.

A summary of the compass corrections is given in Table 4.

Raw Heading	Correction
1.6°	+2.2°
61.6°	+3.1°
121.6°	+2.2°
181.6°	+2.6°
241.6°	-2.2°
301.6°	+0.2°

Table 4: Compass Corrections vs. Heading

A second much larger correction must be added to the raw heading to convert from headings relative to magnetic north to headings relative to true north. These were obtained from navigation maps and vary widely depending on the geographical position, for example, from 11 degrees in the eastern Atlantic to as much as 25 degrees near the U.S. east coast. It is not known how well these are known, or if there are major local disturbances that are not included in the maps. A map of the world showing the magnetic deviations is shown in Figure 7.

During the cruises periodic checks were made between the ship's speed and heading and that as measured by the fish. Some of these are given in Table 5. The headings from the fish have had all corrections incorporated and are headings relative to true north while the headings of the

Ship		Towed Log	
Speed (knots)	Heading (degrees)	Speed (knots)	Heading (degrees)
8.12	320.7	7.96	317.0
10.15	322.6	10.00	317.5
10.16	95.0	10.12	95.4
10.21	103.6	10.29	101.5
10.24	280.4	9.88	277.0
8.03	179.5	8.33	179.5

Table 5: Comparison of Speed and Heading

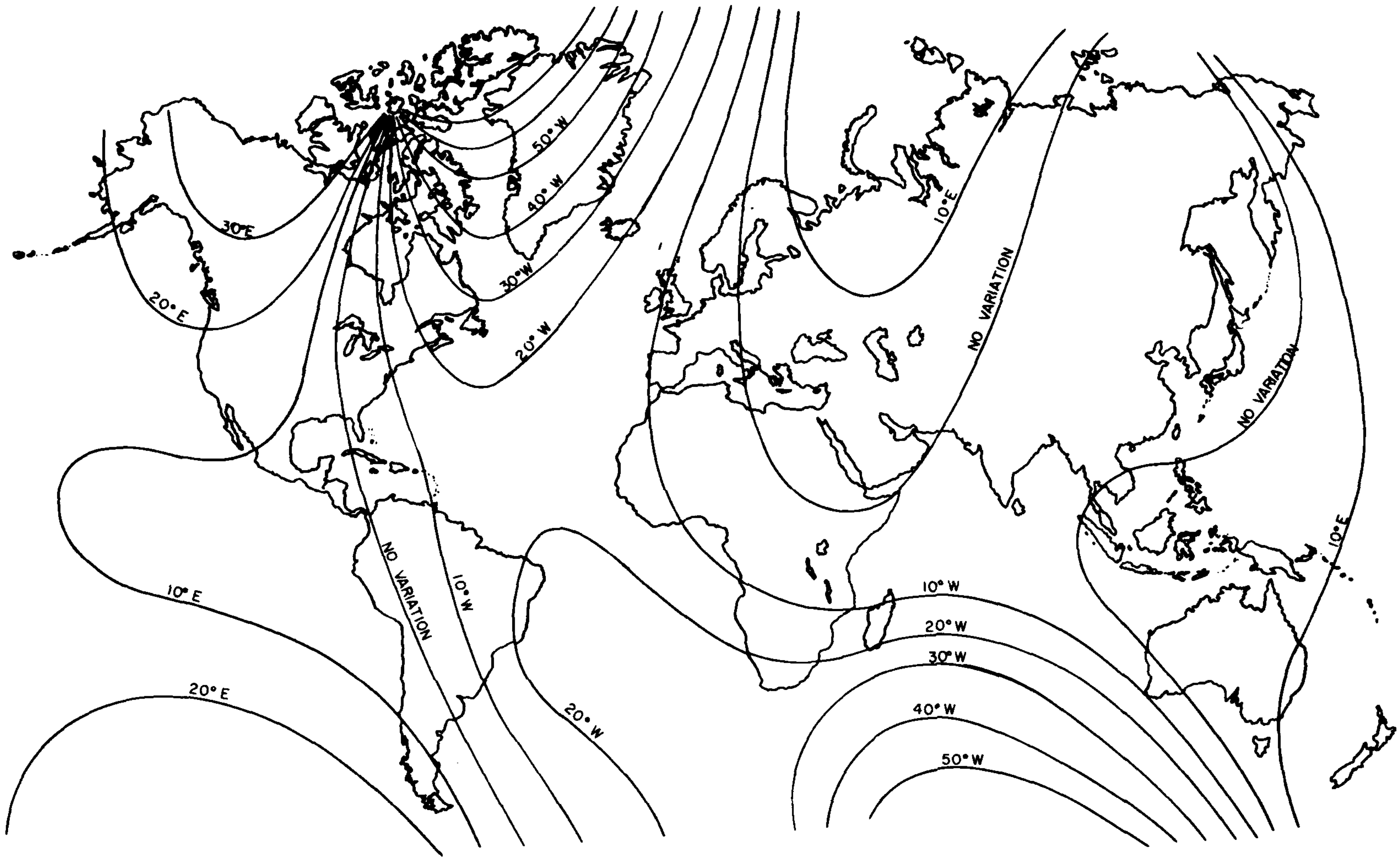


FIGURE 7: MAGNETIC NORTH DEVIATION FROM TRUE NORTH

ship have been corrected for any athwartship speed. Clearly there is very close agreement in speed, but there are sizeable discrepancies in heading. The ship measurements were essentially instantaneous readings, while those of the towed log were ten second averages. Over this time interval, with 300 meter separation in measurements, discrepancies of this magnitude are not unreasonable and this comparison is a good qualitative check of the towed log sensors.

During the SHACKLETON cruise there was an opportunity to make some runs at different speeds and headings by one of the JASIN drifting moorings. The fish was towed while the ship's position relative to the drifter was monitored by periodically measuring its range and bearing with radar. These positions were then plotted along with the dead reckoned positions as measured by the fish and are shown in Figures 8a through 8d. The track of the ship as determined from the towed log is shown by the solid line and plusses while the position as calculated from the range and bearing information is shown by the asterisks. By using a drifter as a reference the effects of currents are eliminated.

The results are somewhat inconclusive. There appears to be a constant bias in the heading with the towed log indicating a 1.8° to 4.5° numerically lower reading. This could be due to actual errors in the sensor itself or in the corrections used to convert from a magnetic north to true north reference point. These runs were made at 59°12.1'N and 13°16.2'W and the magnetic correction used was 16.4°. Although the ranges and bearings from the radar were taken manually, they appear to be consistent so they are probably accurate enough to use as a reference.

In comparing the distance run to the radar positions, the first dead reckoned position is always much closer to the start position than the first

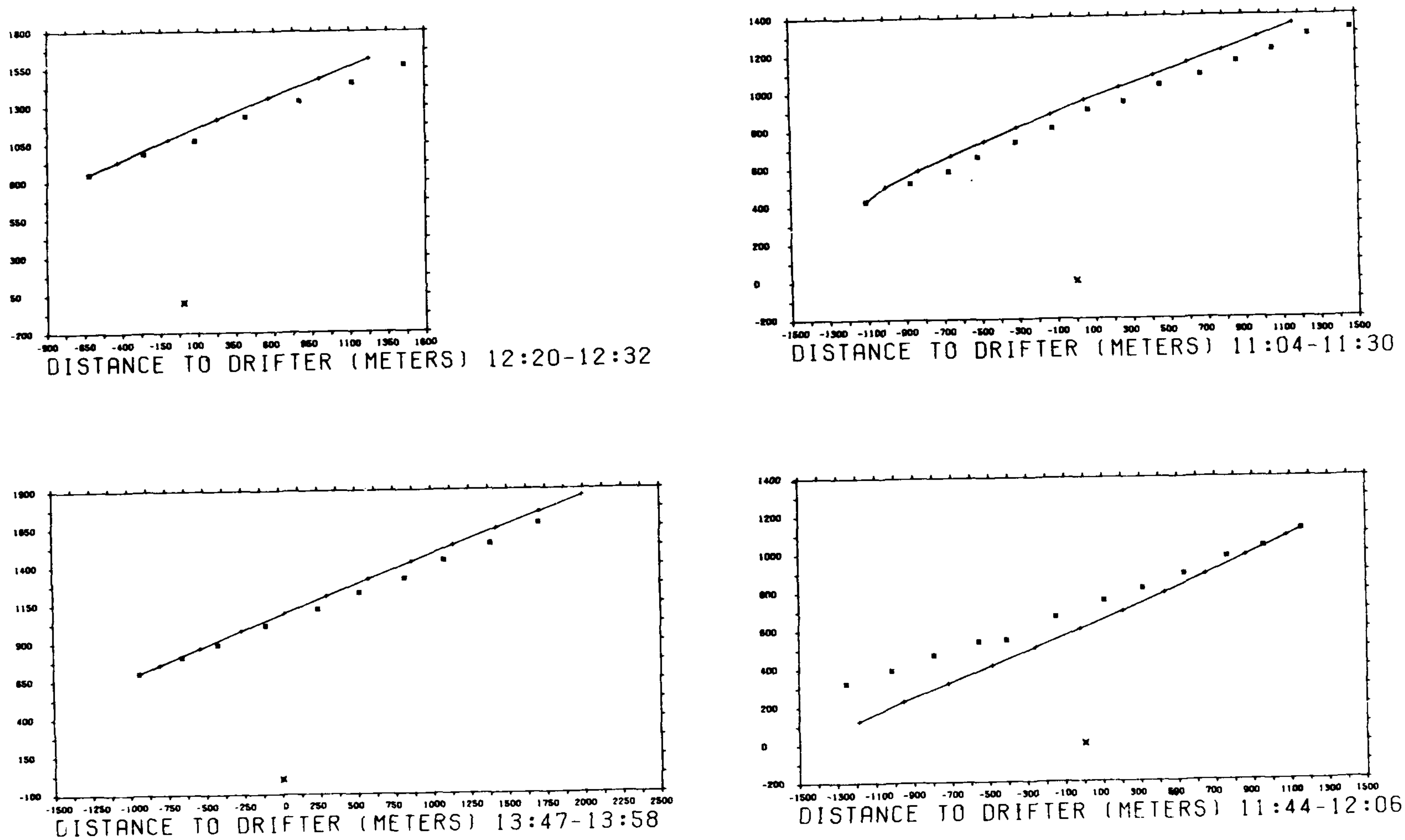


FIGURE 8 SHIP TRACK VERSUS RADAR POSITIONS

radar position. It is possible that the fish has not stabilized from the turn made just prior to the start of the run, so in comparing the two the start position was eliminated. The errors in the towed log speed range from -5.5% to +5.9% with no consistent pattern although this would be hard to detect with only four trials.

CALCULATION OF SURFACE CURRENTS

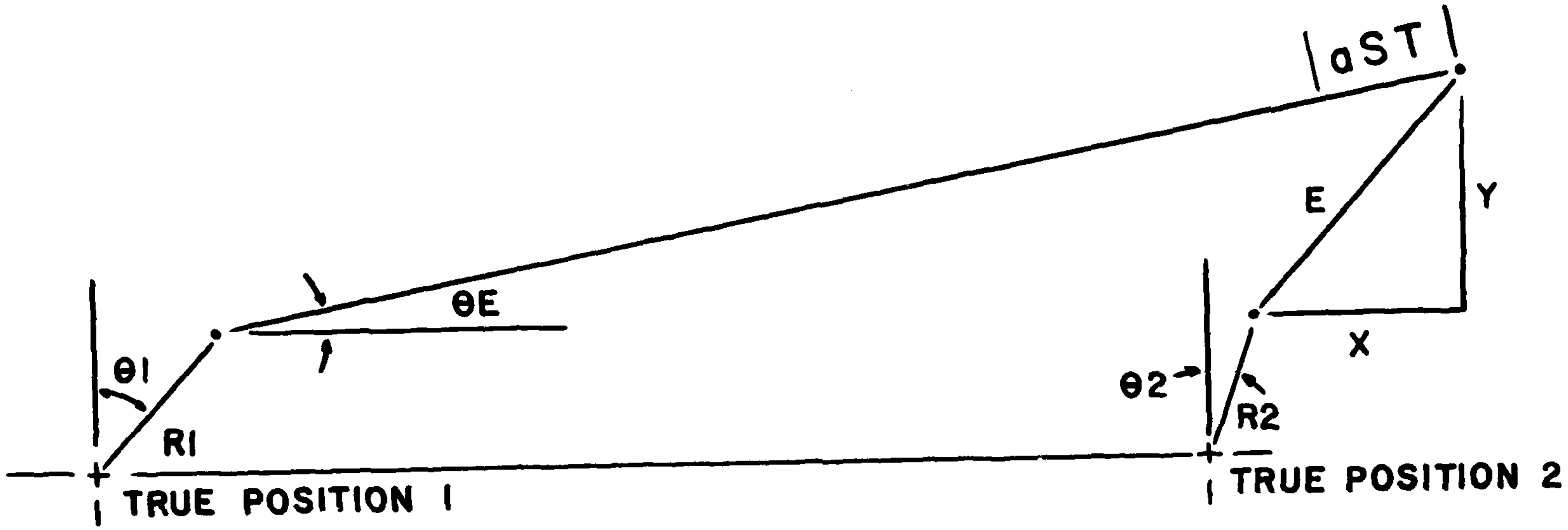
Calculations of the surface currents were carried out using both Loran C and satellites for reference navigation positions. Starting from an initial reference position the north and east components of speed for each second were summed until the time coincided with that of the next reference position. Every 100 seconds the geographical position was calculated in order to update the magnetic-to-true north correction factor.

When the time coincided with that of the second fix, the distance and heading from the dead reckoned position to the reference position were calculated using simple flat plane geometry and then converted to current speed and direction by dividing the distance by the time difference between the two reference navigation positions.

In converting distance run to latitude and longitude, the earth was assumed to be circular along lines of constant latitude and an ellipse along lines of constant longitude with polar and equatorial radii of of 6.357×10^6 and 6.378×10^6 meters respectively.

ERROR ANALYSIS

Figure 9 illustrates the factors to be considered when determining the errors in measuring the surface currents. Assuming that the true current is zero and that there are no errors in measuring speed, heading and reference positions, then by steaming from position 1 to position 2 the



R1 = NAVIGATION ERROR 1
R2 = NAVIGATION ERROR 2
a = SPEED ERROR - PER CENT
S = SHIP SPEED
T = TIME BETWEEN FIXES

FIGURE 9: SURFACE CURRENT ERRORS

dead reckoned and reference position 2 will coincide and the calculated current will be zero. Now consider the case where there are errors in all three parameters. By breaking each error into its X and Y components and summing yields

$$X = R1\ \sin(\Theta 1) - R2\ \sin(\Theta) + aS\ T$$

$$Y = R1\ \cos(\Theta 1) - R2\ \cos(\Theta 2) + s\ \sin(\Theta E) T$$

Then $\overline{E^2} = \overline{X^2 + Y^2}$

and setting $\overline{R1} = \overline{R2} = 0$ and $\sin(\Theta E) = \Theta E$ gives

$$\overline{E^2} = \overline{R_1^2} + \overline{R_2^2} + T^2 S^2\ (\overline{a^2} + \overline{\Theta E^2}) = 2\overline{R^2} + T^2 S^2\ (\overline{a^2} + \overline{\Theta E^2})$$

For simplicity assume the speed and heading have error bounds of $\pm a$ and $\pm\Theta$ and that these errors have a uniform distribution between these two limits. Then

$$\overline{a^2} = a^2/3 \text{ and } \overline{\Theta E^2} = \Theta^2/3$$

which gives the following expression for the RMS error

$$E(\mathrm{RMS}) = \sqrt{\overline{E^2}} = (2\overline{R^2}/\ T^2 + S^2(a^2/3 + \Theta^2/3))^{1/2}$$

It can be seen that the total error is composed of the error due to navigation, $2\overline{R^2}/T^2$, and the error due to speed and heading, $S^2(a^2/3 + \Theta^2/3)$.

Tests have been done at Woods Hole to get an idea of the navigation errors. A Magnavox 706 satellite navigation set was run at a fixed position and statistics on the distribution of fixes were computed as shown in Table 6. Limits were set for the maximum and minimum elevation angles and the maximum number of iterations and any fixes not falling within this range were not used in the calculations. The RMS error and the radius of a circle (CEP) around the mean position which would include 50% of the fixes were determined.

Elevation Min	Elevation Max	Iterations Max.	Fixes	$\overline{R^2}$ Meters	CEP Meters
10	75	4	58	95.2	61.5
10	75	3	83	83.9	57.4
15	75	4	56	87.6	59.3
10	75	3	59	79.0	59.7
5	75	4	64	99.2	69.5

Table 6: Satellite Fix Error (10)

Similarly a several hour long sample of Loran C positions using a Northstar Model 6000 receiver was accumulated with the receiver in a fixed position. Logging and analysis was all done manually so a simpler calculation was made than was done for the satellites. The average and RMS distance between successive fixes for several combinations of slaves were computed and are shown in Table 7.

Slave Stations*	Avg. Displacement	RMS Displacement
S1-S2	29.4 m	33.7 m
S1-S3	40.3	48.9
S2-S3	45.7	51.9

*S1 = Caribou, Maine; S2 = Nantucket, Mass.; S3= Carolina Beach, N.C.

Table 7: Loran C Errors

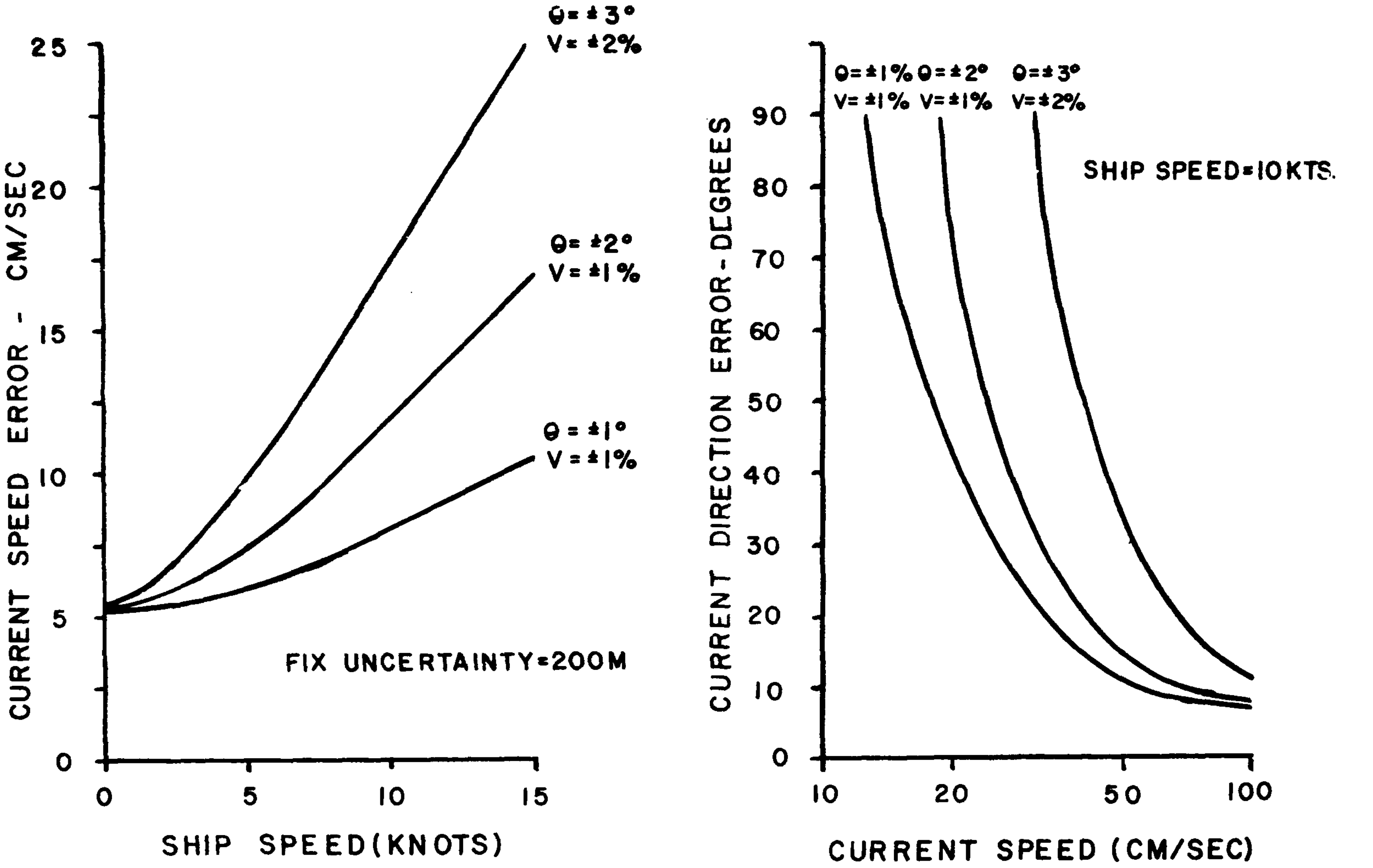
Admittedly these tests were run under ideal conditions and operation of the receivers at sea would be somewhat less satisfactory, but it gives an idea of the order of magnitude of the expected errors.

The RMS error of the current direction is difficult to calculate and instead a worst case analysis can be done more easily. The gruesome details of this are omitted here, but plots of current magnitude and direction errors for various speed and heading errors are plotted in Figure 10. It can be seen that as the current speed goes up or the ship speed decreases, the error in current direction is reduced. This is obvious since one would expect stronger currents to stand out more definitely.

FIGURE 10

COMBINED RMS SPEED ERROR

WORST CASE DIRECTION ERROR



CRUISE RESULTS

During the past two years the towed log was used at sea on six separate occasions under various ship and sea conditions. Following the construction and final testing of the system at IOS in England, it was used aboard the RRS SHACKLETON for the first leg of the JASIN experiment and then transferred to the R/V ATLANTIS II for the transit back to Woods Hole. During May and June of 1979 the system was used aboard the R/V GYRE during its NORPAX shuttle run from Hawaii to Tahiti.

In the fall of 1979 it was again deployed from the R/V ATLANTIS II and towed from Woods Hole to Fortaleza, Brazil, and in December it was used aboard the R/V OCEANUS during Dr. V. Worthington's Gulf Stream transport studies in the North Atlantic.

Finally, it was deployed from the R/V THOMAS WASHINGTON during the Pacific Fronts experiment in February 1980, but unfortunately very little useful data was obtained since the instrument was damaged during a rough weather deployment.

The data from each of these cruises are displayed and discussed on the following pages.

SHACKLETON CRUISE RESULTS (28 July - 19 August 1978)

The towed log was deployed off and on throughout the first leg of the JASIN exercise for a total of about 120 hours. There were no major problems other than the radio interference problem mentioned earlier and this was taken into account when writing the data reduction computer programs to eliminate most of the errors it may have introduced into the calculations. Listings and plots of the derived currents are shown for each tow period. The current speed in the listings is in centimeters/second and the direction is in degrees. The reference navigation fixes are plotted as asterisks with the arrow indicating current direction and relative magnitude.

It was thought prior to the field tests that the towed log would operate most satisfactorily under a steady tow where severe ship maneuvers were kept to a minimum and the SHACKLETON data seems to verify this.

The ship left Glasgow on July 28, 1978 for the JASIN area and the system was first deployed the next day (210) when it was towed for approximately 12 hours. A very strong northeast current was encountered during the tow as shown in the first point. A second extended tow was made on days 215 and 216 when the ship made a run into Stornoway. The tow in was made during day 215:1600 to day 216:1130. On both of these tows the same strong northeast current was found east of 10°W. A third extended tow was made on the return to Glasgow from day 229:0200 to day 230:1200. Again the northeast flow was found, most strongly east of 11°W.

Although the true magnitude of the current is unknown, the tows on days 215 and 216, which were made in opposite directions, gave roughly the same values which would argue against a major bias to the heading as was observed in the drifter runs.

SHIP: SHACKLETON
TIME: 210:1000 - 210:2100
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
210:11:15: 9	57	5.25	8	32.43	69	48
210:11:32:23	57	8.60	8	36.75	57	29
210:11:48: 0	57	1082	8	39.65	73	31
210:13:17: 9	57	22.54	8	56.55	61	47
210:15: 3:60	57	36.76	9	16.31	42	32
210:17:12: 0	57	55.53	9	41.41	77	23
210:18: 7: 9	58	2.2	9	53.1	81	25
210:18:59: 9	58	8.33	10	3.50	79	48
210:19:52: 0	58	15.25	10	14.33	72	33
210:20:26: 0	58	20.84	10	20.24	99	50

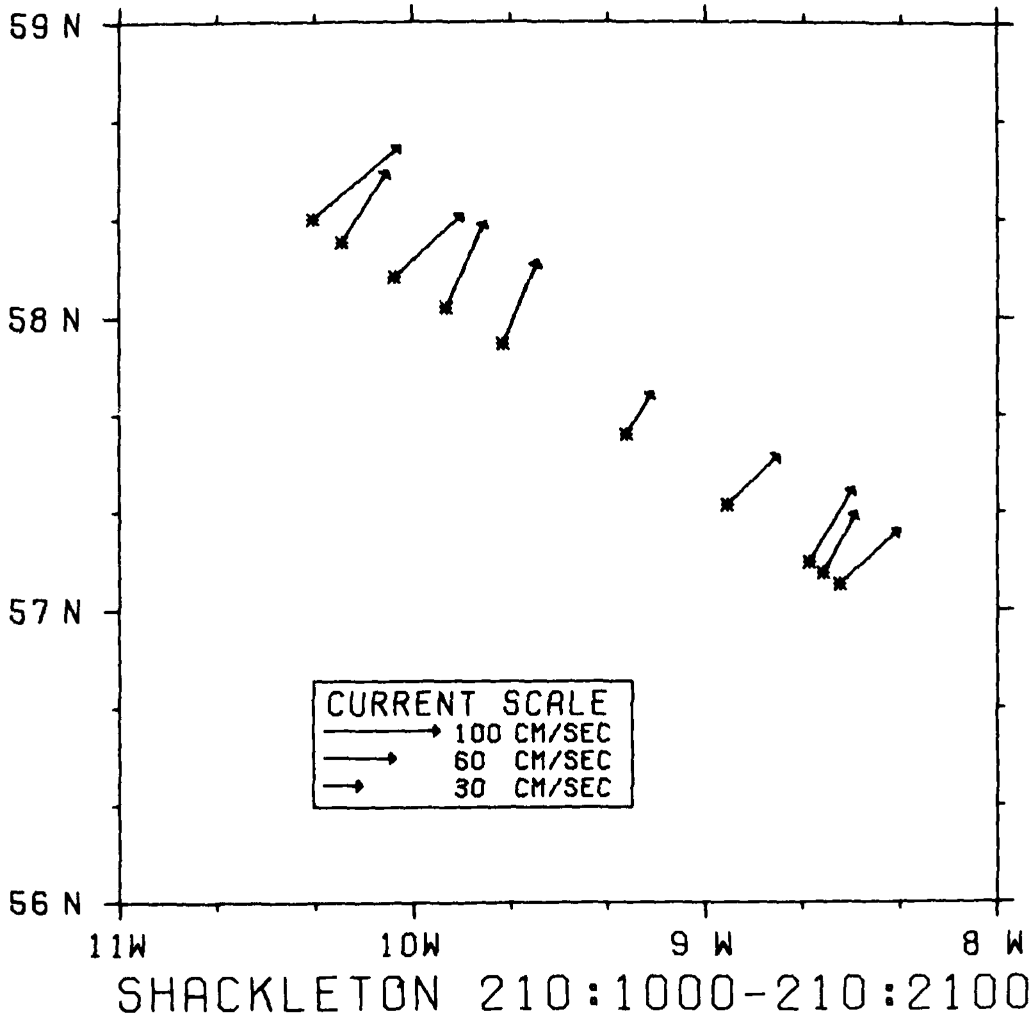


FIGURE 11: SHACKLETON SURFACE CURRENTS

SHIP: SHACKLETON 1978
TIME: 215:0100 - 215:0900
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
215: 0: 1: 9	58	43.73	10	14.97	18	112
215: 2: 6:46	58	37.28	9	34.81	89	321
215: 2:43: 9	58	35.42	9	22.10	56	52
215: 3:27:60	58	33.35	9	8.38	43	9
215: 5:36:23	58	29.49	8	27.93	41	25
215: 6:57: 9	58	26.26	8	1.41	29	17
215: 7:26: 0	58	26.51	7	52.26	44	360
215: 7:41:60	58	25.13	7	47.25	46	354
215: 9:14:23	58	23.58	7	17.46	46	22

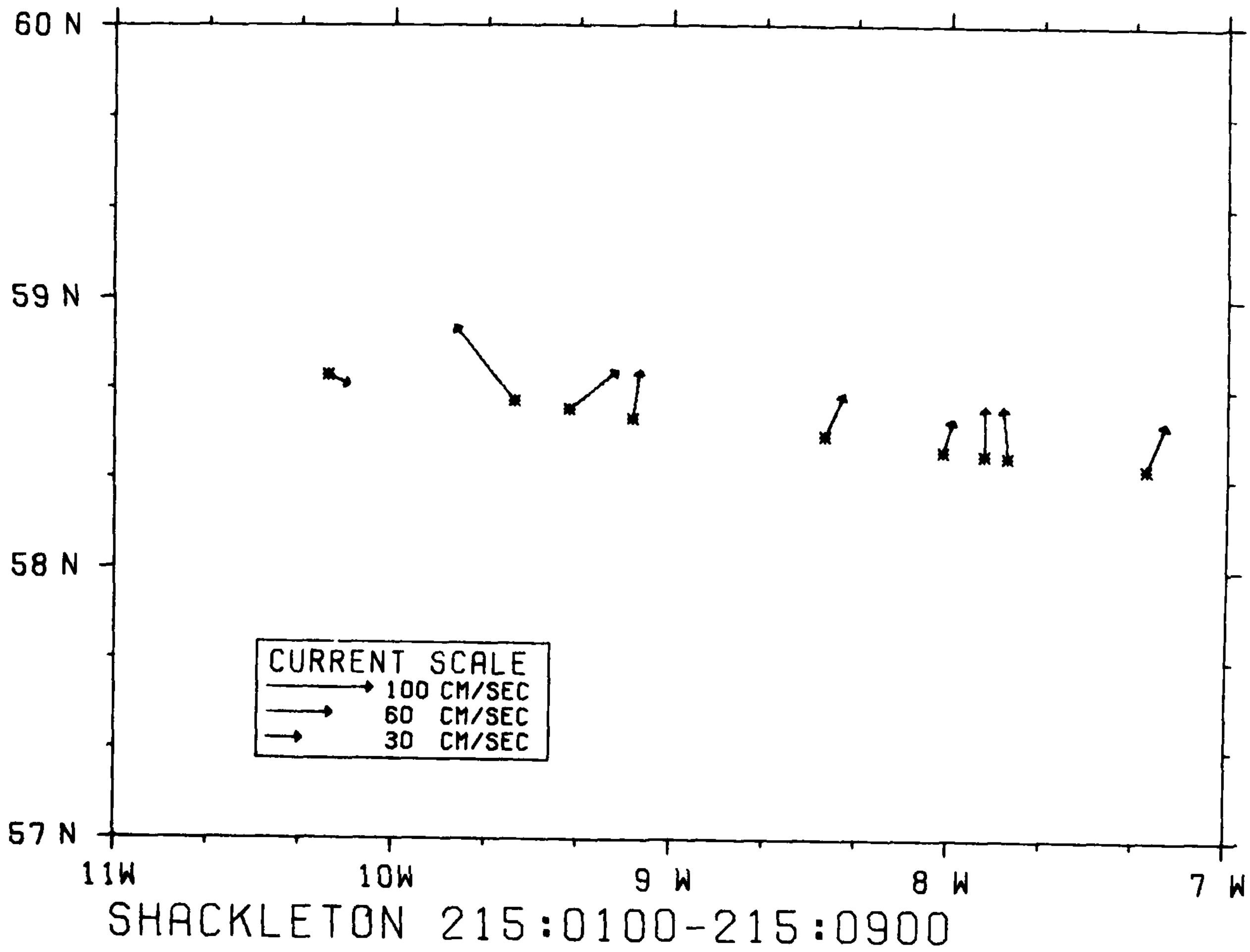


FIGURE 12: SHACKLETON SURFACE CURRENTS

SHIP: SHACKLETON 1978
TIME: 215:1600 - 216:1100
NAVIGATION: LORAN C

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
215:15:59:60	58	28.48	7	51.31	50	52
215:18: 0: 0	58	33.3	8	28.20	43	38
215:20: 0: 0	58	38.97	9	6.50	70	25
216: 0: 0: 0	58	50.76	10	21.46	39	19
216: 2: 0: 0	58	55.1	11	07	37	6
216: 3:59:60	59	2.41	11	37.45	52	21
216: 6: 0: 0	59	5.74	12	6.64	48	34
216: 8: 0: 0	59	12.95	12	42.85	45	7
216: 9:59:60	59	19.28	13	11.22	39	14
216:11: 0: 0	59	27.26	13	22.85	72	45

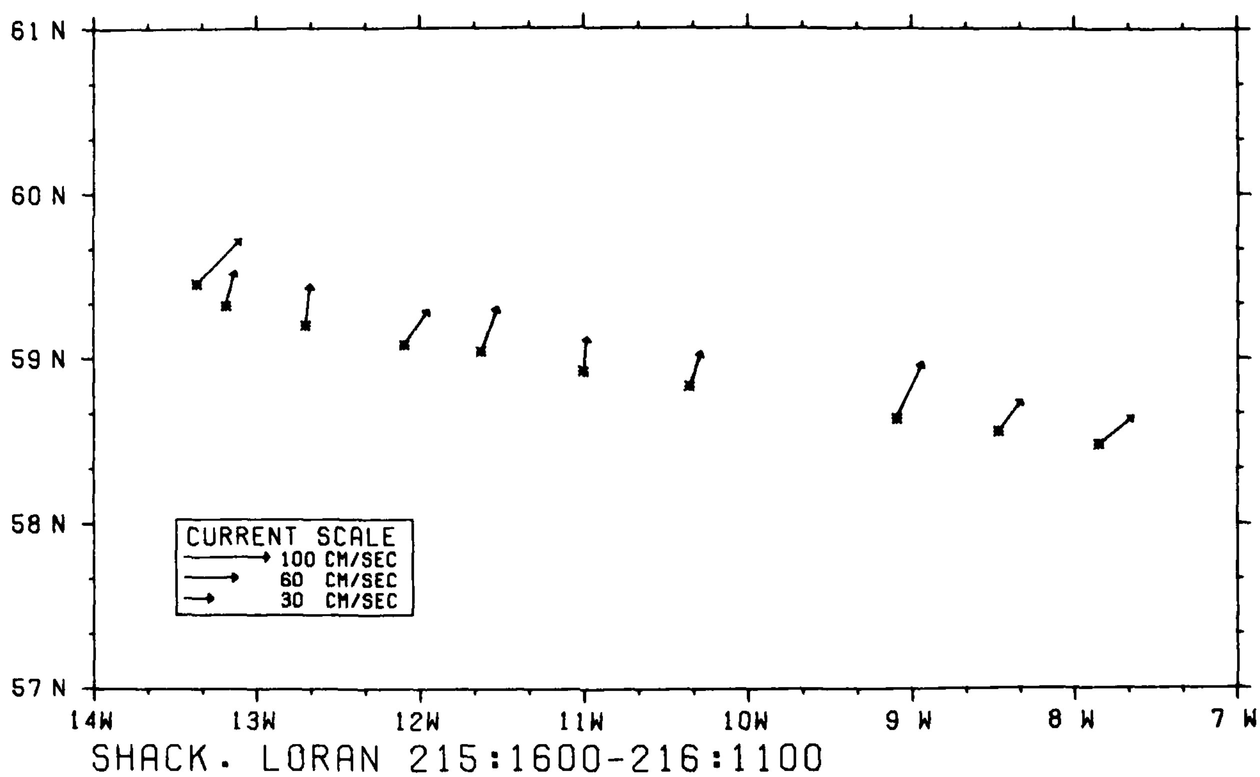


FIGURE 13: SHACKLETON SURFACE CURRENTS

The tow on 217 was made under very confused conditions with a major ship maneuver during almost every current calculation. Both the first part of this tow and the following one on days 223 and 224 were made in the vicinity of the JASIN Fixed Intensive Array. A comparison with a VACM moored at 17 meters depth which most closely duplicates the towing depth of the fish was not very revealing. According to the VACM on days 223 and 224, the flow was directly to the north with a magnitude that ranged between 20 and 50 centimeters per second. The towed log seems to indicate a northward flow on the western side of the pattern and a southward flow on the eastern side.

SHIP: SHACKLETON JASIN 1978
TIME: 217:0000 - 217:1400
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
217: 0:30: 0	59	1.10	12	39.60	27	238
217: 2:15: 9	58	56.18	12	22. 4	14	6
217: 3:58:23	59	4.80	12	36.81	30	317
217: 5: 8:23	58	56.86	12	39.45	20	307
217: 7:35: 9	59	4.11	12	28.83	29	13
217: 8:40:46	59	6. 8	12	46.61	81	7
217: 9:38:46	59	9.22	13	1.65	64	35
217:10:46:23	59	12. 2	13	16.82	25	330
217:11: 9: 9	59	12.10	13	15.62	52	80
217:12:30:46	59	13.53	13	14.21	22	274
217:13:10:23	59	12.33	13	15.16	14	162
217:14:16:46	59	12. 9	13	16.17	22	358

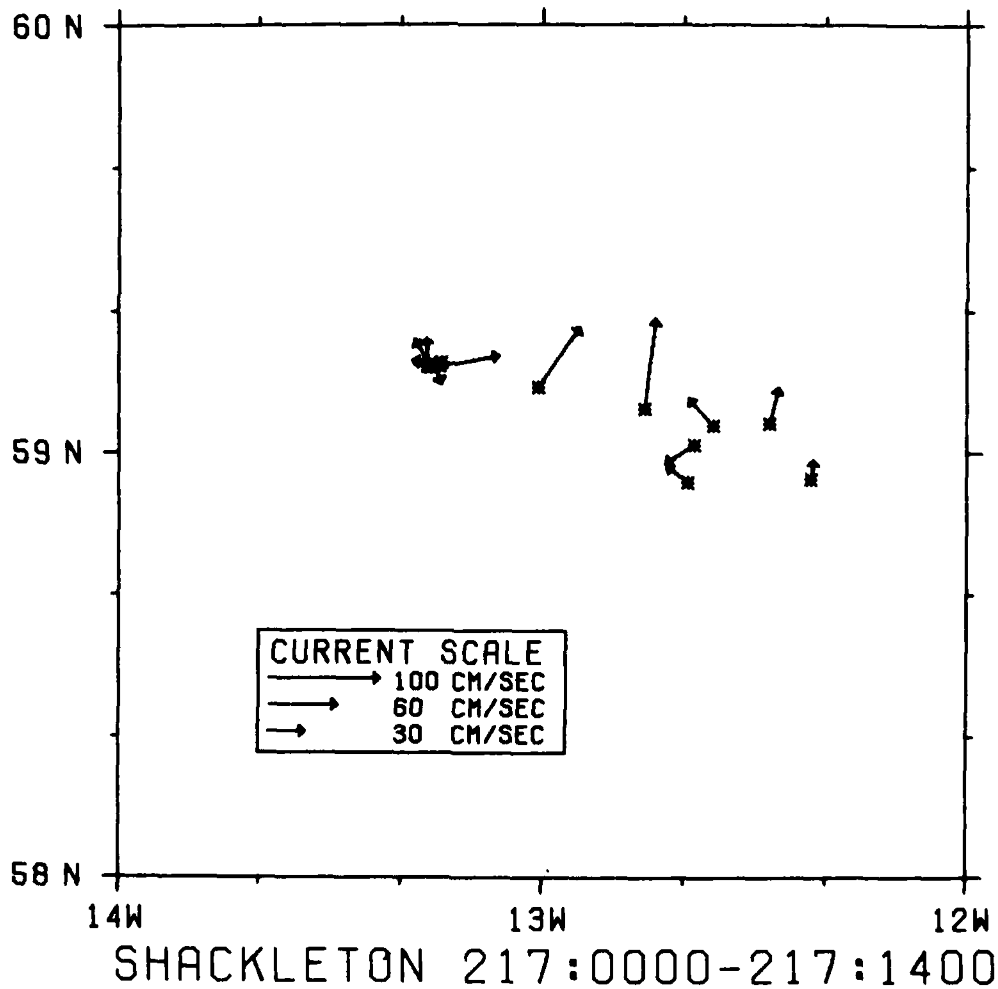


FIGURE 14: SHACKLETON SURFACE CURRENTS

SHIP: SHACKLETON 1978
TIME: 223:1700 - 224:1100
NAVIGATION: LORAN C

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
223:17: 0: 0	59	8.64	13	9. 94	18	254
223:18: 0: 0	59	1.19	13	9. 64	44	353
223:18:59:60	58	55.73	13	8. 80	10	41
223:20: 0: 0	58	48. 4	13	8. 93	21	23
223:21: 0: 0	58	41.84	13	9. 8	23	24
223:21:59:60	58	38.29	12	57.35	72	177
224: 3: 0: 0	58	43.70	11	51.1	30	321
224: 3:59:60	58	52.75	11	51.98	33	187
224: 5: 0: 0	59	1.85	11	51.65	26	156
224: 6: 0: 0	59	1089	11	50.25	24	176
224: 6:49:60	59	17.37	11	50.47	33	192
224: 7: 9:60	59	19.24	11	53.66	80	215
224: 9: 0: 0	59	19.23	12	24.85	59	15
224: 9:59:60	59	20.61	12	41.12	25	26
224:11: 0: 0	59	20.83	12	58.8	32	24

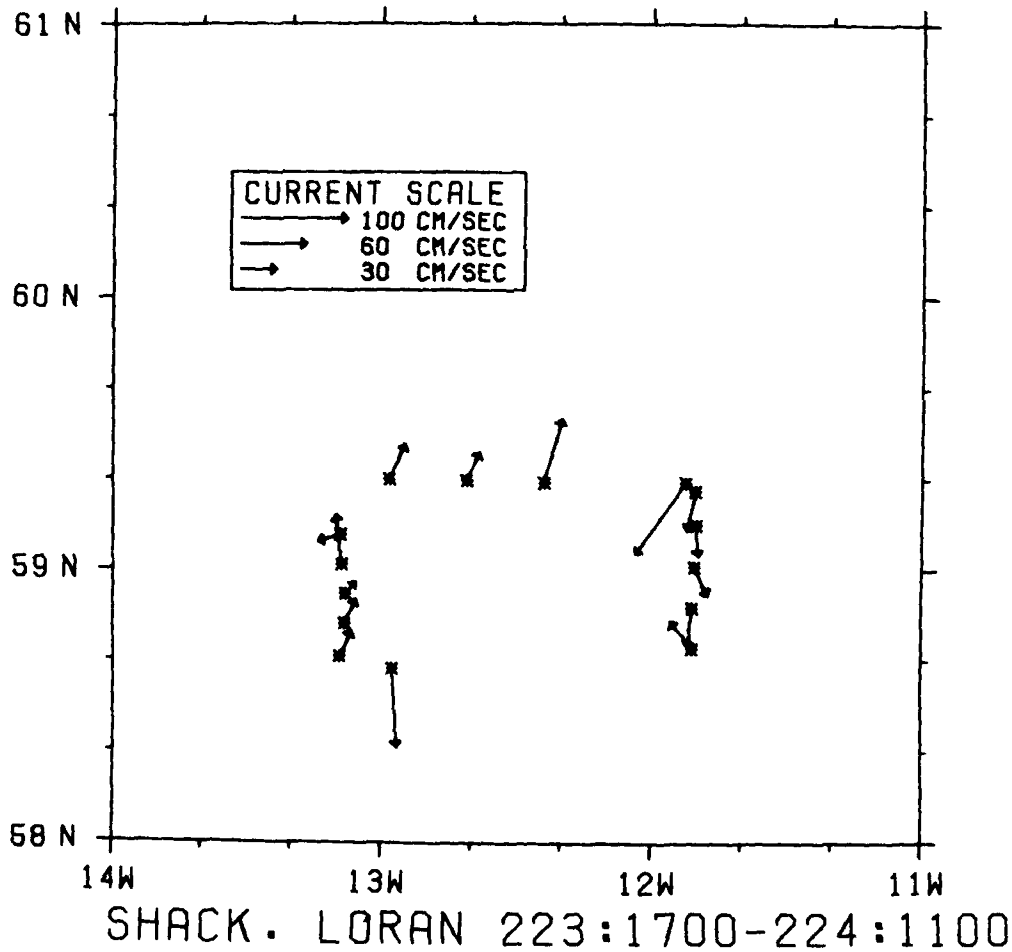


FIGURE 15: SHACKLETON SURFACE CURRENTS

SHIP: SHACKLETON 1978
TIME: 229:0200 - 230:0400
NAVIGATION: LORAN C

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
229: 3:49:60	58	59. 5	12	19.43	27	342
229: 4:19:60	59	4.90	12	19.43	17	246
229: 4:50: 0	59	4.12	12	28. 3	32	258
229: 5:19:60	59	4.22	12	37. 1	40	9
229: 6:30: 0	59	5. 6	12	46.61	14	43
229: 7:40: 0	58	54.79	12	46. 5	5	32
229: 8:10: 0	58	52.36	12	40.25	58	18
229: 9:20: 0	58	52. 9	12	18.94	9	44
229: 9:59:60	58	49.52	12	8.33	14	167
229:12: 0: 0	58	35.73	11	43.70	20	60
229:14: 4:60	58	21.21	11	17. 4	25	47
229:15:59:60	58	1063	10	55.84	44	50
229:18: 0: 0	57	58.24	10	32.91	100	68
229:20: 0: 0	57	47.29	10	11.92	43	43
229:21:59:60	57	35.44	9	50.49	45	53
230: 0: 0: 0	57	24.13	9	30.87	23	67
230: 2: 0: 0	57	13.52	9	8.25	26	49
230: 3:59:60	57	1. 8	8	45.12	56	49

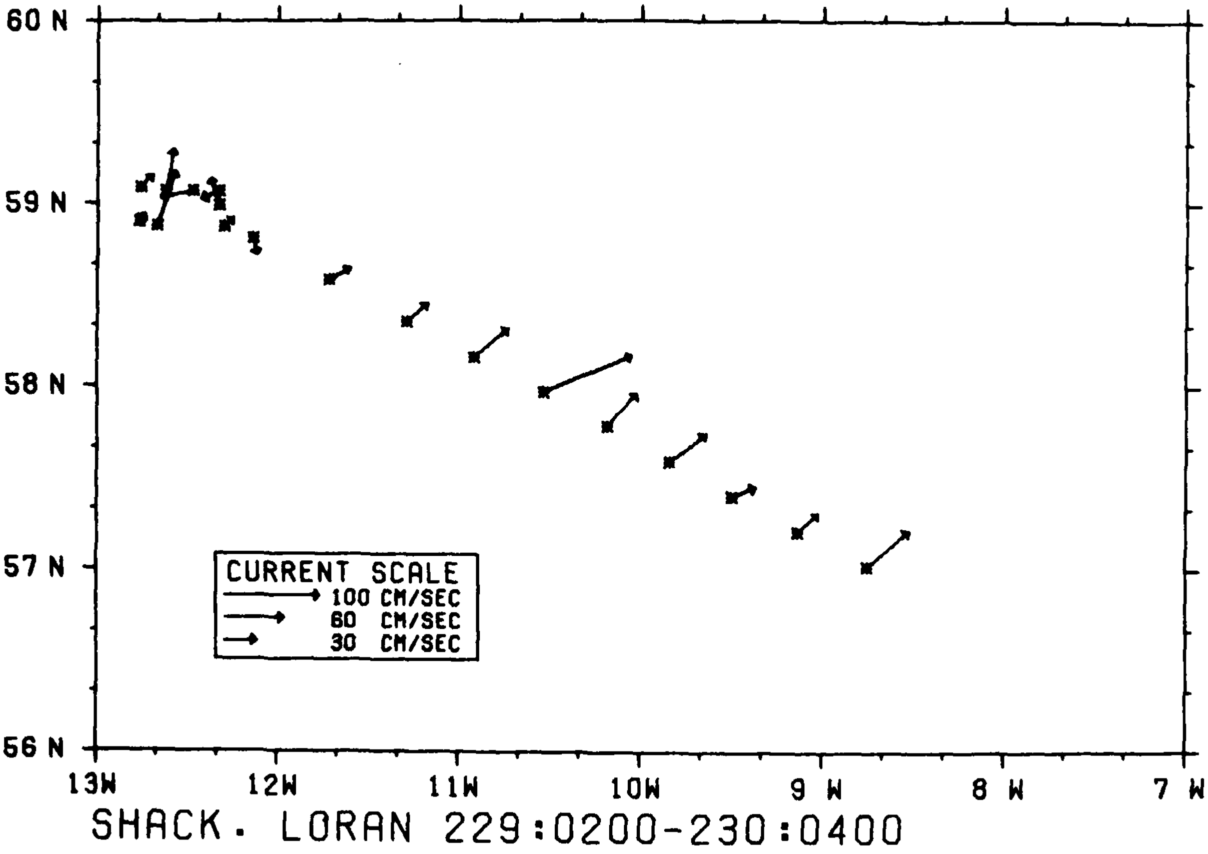


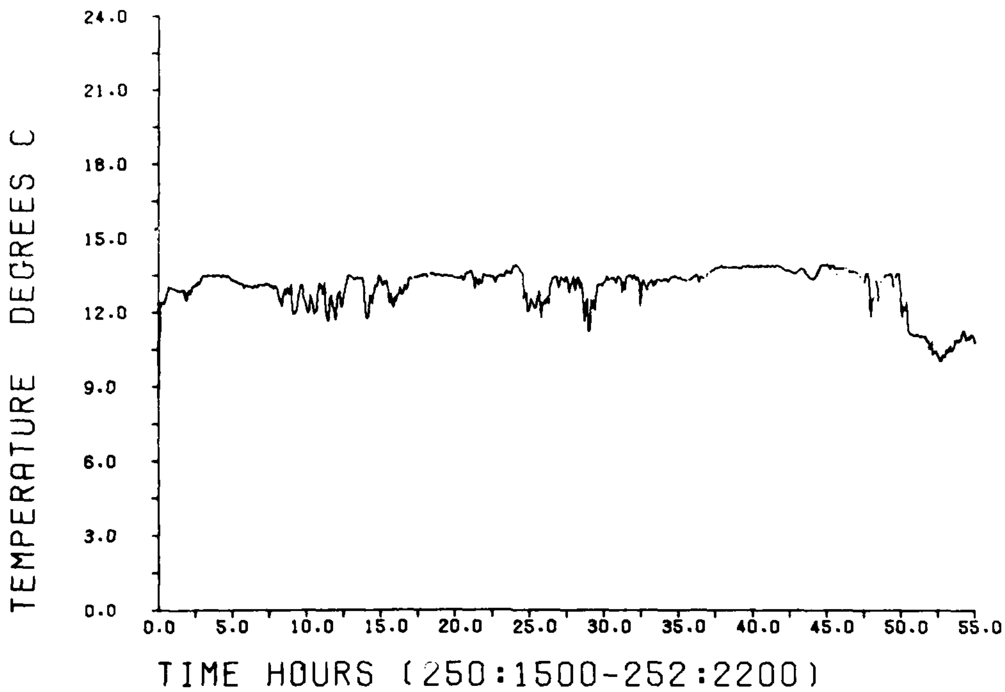
FIGURE 16: SHACKLETON SURFACE CURRENTS

ATLANTIS II CRUISE RESULTS (21 August - 23 September 1978)

Following the SHACKLETON cruise the gear was transferred to the ATLANTIS II in Glasgow and the ship left for the JASIN area on August 21, 1978. During the JASIN exercises the system was not deployed, but following the last operation on September 7 (day 250) it was put in the water and the transit for Woods Hole was begun. Operation was normal until severe weather conditions were encountered on the evening of day 252 when the tow cable began to develop sea water short circuits due to damage it had sustained during a deployment on the SHACKLETON. The fish was retrieved, about 30 meters of cable removed, and new electrical and mechanical terminations installed. Weather conditions remained very bad until day 257 (September 14) when the system was redeployed and towed without incident until day 263 (September 20) when the bridge officers requested that it be brought in to prevent fouling fishing gear in the area.

Plots and listings of the surface currents are shown on the following pages along with the temperature profile. The currents derived using Loran and the satellites agreed well throughout most of the transit. During the initial days of the cruise, days 250-252, there was little activity until the last five hours of the plot when a moderately strong northwesterly flow was indicated. A drop in the water temperature was noted for this same time period.

Following the four day gap for cable repairs, a highly energetic region was encountered during days 257-261. A comparison of the temperature data with the currents shows a fairly high correlation with northerly currents corresponding to the low temperatures possibly indicating the intrusion of colder water from the north, while the temperature peaks match up pretty well with flows to the north and west.



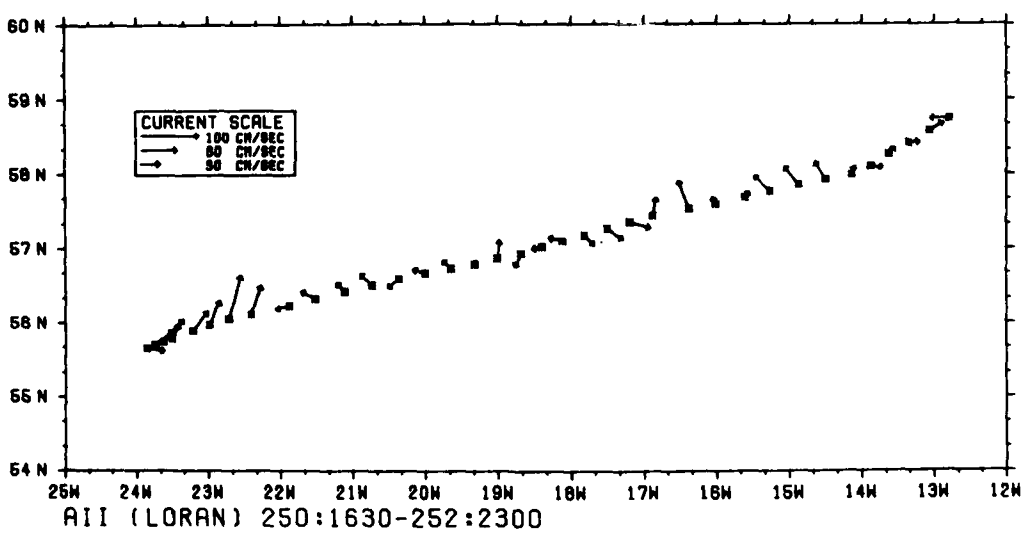
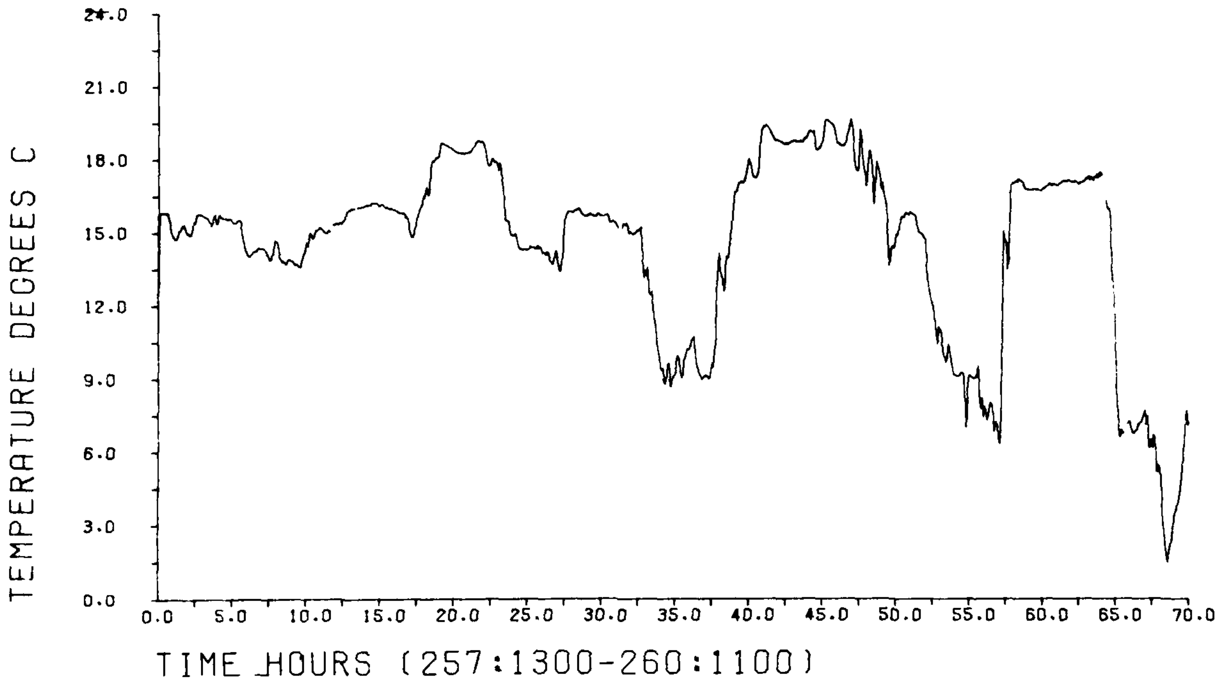


FIGURE 17: ATLANTIS II 1978 SURFACE CURRENTS AND SURFACE TEMPERATURE

SHIP: ATLANTIS II JASIN 1978
TIME: 250:1700 - 252:2300
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
250:17:15:60	58	39.38	12	55.34	5	13
250:19: 4: 0	58	28.51	13	16.59	15	70
250:21:22: 0	58	13.12	13	42.73	8	71
250:23:17:60	58	1.76	13	59.60	17	98
251: 1: 4: 0	57	57.52	14	23.97	29	340
251: 3:49:60	57	48.33	15	5. 0	36	319
251: 5:36: 0	57	42.43	15	31.79	17	322
251: 7:50: 0	57	35.73	16	7.52	11	333
251: 9:33:60	57	29.43	16	37.49	81	283
251:11:17:60	57	25.37	16	57.28	94	64
251:13: 6: 0	57	19.10	17	19. 10	35	114
251:14:48: 0	57	13.83	17	41.97	21	140
251:18:18: 0	57	2.14	18	22.34	8	273
251:19:57:60	56	57.51	18	42.80	24	219
251:22: 9:60	56	50. 5	19	8.94	18	9
251:23:56: 0	56	45. 8	19	30.89	9	12
252: 1:41:60	56	41.50	19	54. 9	16	264
252: 2:58: 0	56	38.55	20	13.74	18	273
252: 4:40: 0	56	32.54	20	38.58	21	271
252: 6:25:60	56	25.44	21	4.49	22	324
252: 8:17:60	56	18.27	21	35.77	27	297
252: 8:46: 0	56	16.22	21	42. 6	17	197
252:10:11:60	56	10. 4	22	6.54	9	235
252:11:56: 0	56	4.62	22	30.19	11	21
252:13:45:60	55	58.85	22	53.78	45	10
252:17:19:60	55	46.85	23	27.53	27	24
252:17:56: 0	55	45.60	23	30.35	27	63
252:20:53:60	55	39.63	23	45.40	26	66
252:22:50: 0	55	35.31	23	55.58	31	58



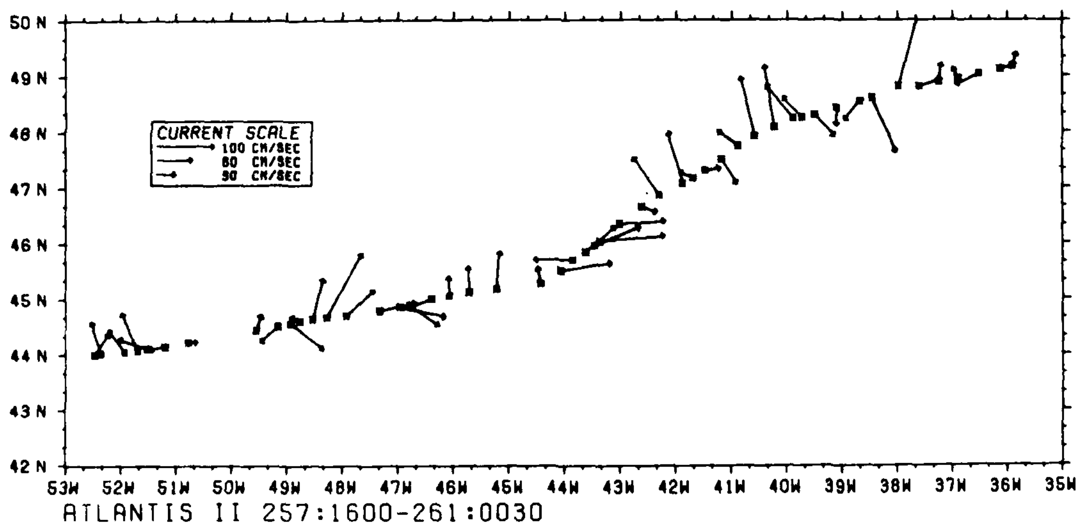
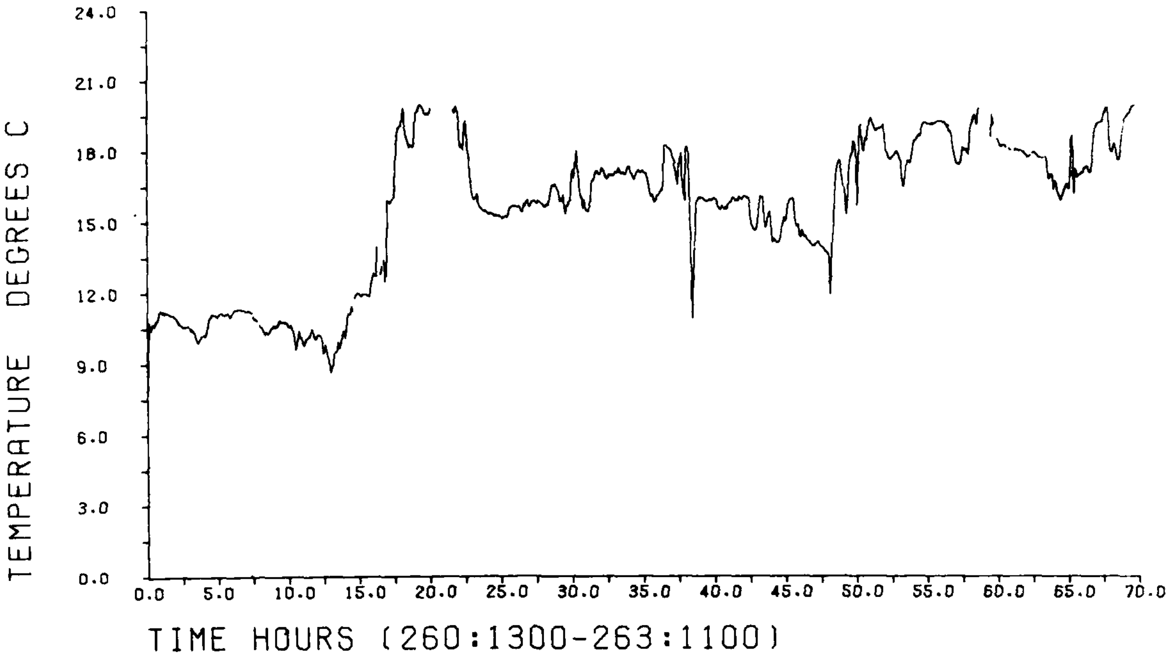


FIGURE 18: ATLANTIS II 1978 SURFACE CURRENTS AND SURFACE TEMPERATURE

SHIP: ATLANTIS II JASIN 1978
TIME: 257:1600 - 261:0030
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
257:16:24: 0	49	1099	35	54. 4	20	16
257:17:30: 0	49	7.19	36	7.26	23	76
257:19: 9:60	49	2.95	36	31.71	42	246
257:20:56: 0	48	57.40	36	54.59	15	333
257:22:33:60	48	53.20	37	15.98	29	9
258: 2: 6: 0	48	49.78	37	59.77	183	16
258: 4:28: 0	48	36.17	38	28.61	103	155
258: 5:23:60	48	32.43	38	41.94	40	219
258: 7: 9:60	48	25.32	39	6.93	28	181
258: 8:58: 0	48	18.89	39	30.64	48	138
258: 9:53:60	48	15.30	39	44.60	46	315
258:10:30: 0	48	14.92	39	53. 7	73	320
258:12:14: 0	48	5.89	40	14.60	107	351
258:14: 1:60	47	55.89	40	35. 6	104	347
258:15:29:60	47	45.87	40	52.28	42	304
258:17:15:60	47	31.64	41	11.50	49	149
258:20: 8: 0	47	10.10	41	41.11	23	293
258:21: 3:60	47	4.24	41	52.25	92	344
258:23:12: 0	46	52.61	42	18.89	78	325
259: 0:58: 0	46	39. 6	42	37.84	24	109
259: 3:36: 0	46	21.93	43	0.41	78	87
259: 6:20: 0	46	2. 8	43	22.91	112	85
259: 7: 2: 0	45	57.32	43	28.73	84	68
259: 8: 6: 0	45	50.27	43	37.43	66	49
259: 9:12: 0	45	42.15	43	51.91	65	270
259:10:50: 0	45	30.50	44	4.13	89	82
259:12:51:60	45	17.59	44	26.78	25	349
259:16:22: 0	45	11.68	45	14.64	63	5
259:18:25:60	45	7. 6	45	43.38	42	358
259:19:53:60	45	4.75	46	5.56	30	357
259:21: 5:60	44	60.99	46	23. 8	44	251
259:22:55:60	44	54.84	46	47.97	59	126
259:23:50: 0	44	51.48	46	58.52	78	102
260: 1:35:60	44	47.34	47	20.63	63	77
260: 4:24: 0	44	42. 6	47	56.53	62	47
260: 6: 5:60	44	40.47	48	17.71	126	29
260: 8:15:60	44	36. 5	48	46.37	14	295
260:10: 0: 0	44	30.29	49	10. 8	37	228
260:11:43:60	44	26.33	49	33.23	25	18
260:17:12: 0	44	13. 8	50	47.84	12	88
260:18:58: 0	44	9.87	51	12.81	25	259
260:20:17:60	44	6.22	51	32.51	49	290
260:21: 1:60	44	5.90	51	42.100	69	337
260:22: 4: 0	44	3.18	51	56.29	45	324
260:23:56: 0	44	1. 1	52	22.95	56	343
261: 0:29:60	44	0.15	52	29.18	42	36



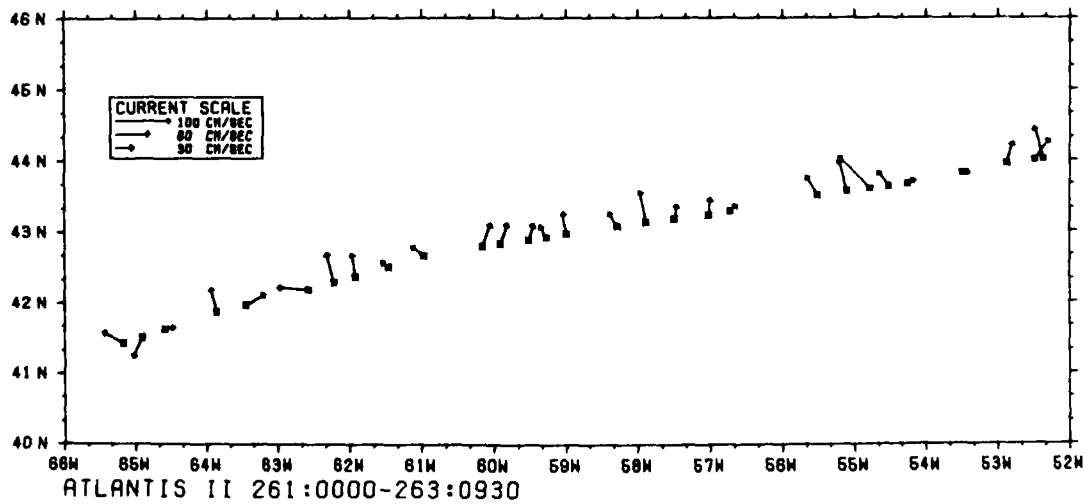


FIGURE 19: ATLANTIS II 1978 SURFACE CURRENTS AND SURFACE TEMPERATURE

SHIP: ATLANTIS II JASIN 1978
TIME: 261:0000 - 263:0930
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
260:23:56: 0	44	1. 1	52	22.96	56	343
261: 0:29:60	44	0.15	52	29.18	42	36
261: 2:15:60	43	57.40	52	53.54	36	16
261: 5:14: 0	43	50.64	53	30.61	9	94
261: 8:45:60	43	40.28	54	15.21	10	65
261: 9:58: 0	43	38.85	54	31. 6	30	323
261:10:59:60	43	36.31	54	47.[illegible]	7[illegible]	315
261:1[illegible]:[illegible]: 0	43	34. 3	55	5. 1	5[illegible]	3[illegible]
261:14: 8: 0	43	31. 3	55	31.68	37	326
261:19:50: 0	43	18.59	56	44.97	12	48
261:21:14: 0	43	14.42	57	2.90	27	7
261:23:23:60	43	11.30	57	30.24	23	10
262: 1: 7:60	43	9.51	57	54.54	55	349
262: 2:54: 0	43	5. 6	58	17.32	26	327
262: 6: 3:60	42	59. 8	58	60.67	36	350
262: 7:17:60	42	56.22	59	17.58	19	333
262: 8:23:60	42	54.78	59	31.24	26	19
262:10: 9:60	42	50.27	59	55.72	37	19
262:11:17:60	42	48. 3	60	1067	40	21
262:14:47:60	42	40.30	60	58.18	24	305
262:17:10: 0	42	31.68	61	28.74	11	308
262:19:22: 0	42	22.31	61	55.33	39	352
262:20:43:60	42	17.37	62	13.43	52	346
262:22:11:60	42	11. 8	62	35.67	54	275
263: 1:46: 0	41	58. 9	63	27.93	37	61
263: 3:34: 0	41	52. 5	63	52.73	42	346
263: 6:51:6C	41	38.53	64	35.12	14	79
263: 8:14: 0	41	31.70	64	54.13	38	206
263: 9:22: 0	41	26.79	65	10.24	39	297

R/V GYRE (11 May - 6 June 1979)

As part of the on-going NORPAX exercises in the Pacific, the R/V GYRE made the shuttle runs between Honolulu, Hawaii and Papeete, Tahiti during the spring of 1979. From Honolulu the ship steamed straight south along 158°W longitude to 3°S latitude, then east to 153°W, north along 153°W to 13°N latitude, east to 150°W longitude, and then straight south along 150°W to Papeete. CTD stations were made only on the N-S tracks at every degree of latitude to within ±3° of the equator where they were made every half degree. With a ship speed of 10 knots, the tow period was normally about six hours for the one degree spacings and three hours in the vicinity of the equator. Except for the equatorial area on the legs along 153°W and 150°W, the towed log was deployed for nearly the entire cruise and a total of about 360 hours of data was accumulated. Navigational coverage was somewhat of a problem in that satellites provided the only coverage, and they tended to come over in clusters twice a day with almost no passes at other times.

One improvement in handling the fish was made on this cruise. In order to avoid interfering with the nightly net tows of the biologists, the large aft end A-frame could not be used for towing. Instead the smaller starboard side A-frame was used which made deployment and recovery much simpler since the fish did not hit the ship when being pulled out of the water.

While there are no strong, stationary currents in the area, it appears as though several features were detected by the towed log. However, there seems to be some inconsistency in the results obtained on the three N-S cruise tracks which may or may not be real. Along the 158°W and 150°W lines there appears to be very little motion from 17°N to 6°N, although the track along 153°W gives some indication of a 10 to 40 cm/sec. eastward current between 7°N and 10°n. Likewise, between 6°N and 2°N the vectors on the 158°W track consistently point to the west while at 150°W they indicate the opposite direction. Since the station spacing only allowed a three hour tow around the equator, only one tow was made in this area along the 158°W leg and it shows an eastward current of 20 to 40 cm/sec.

South of the equator all the vectors indicate a fairly strong (40 to 60 cm/sec.) westward flow.

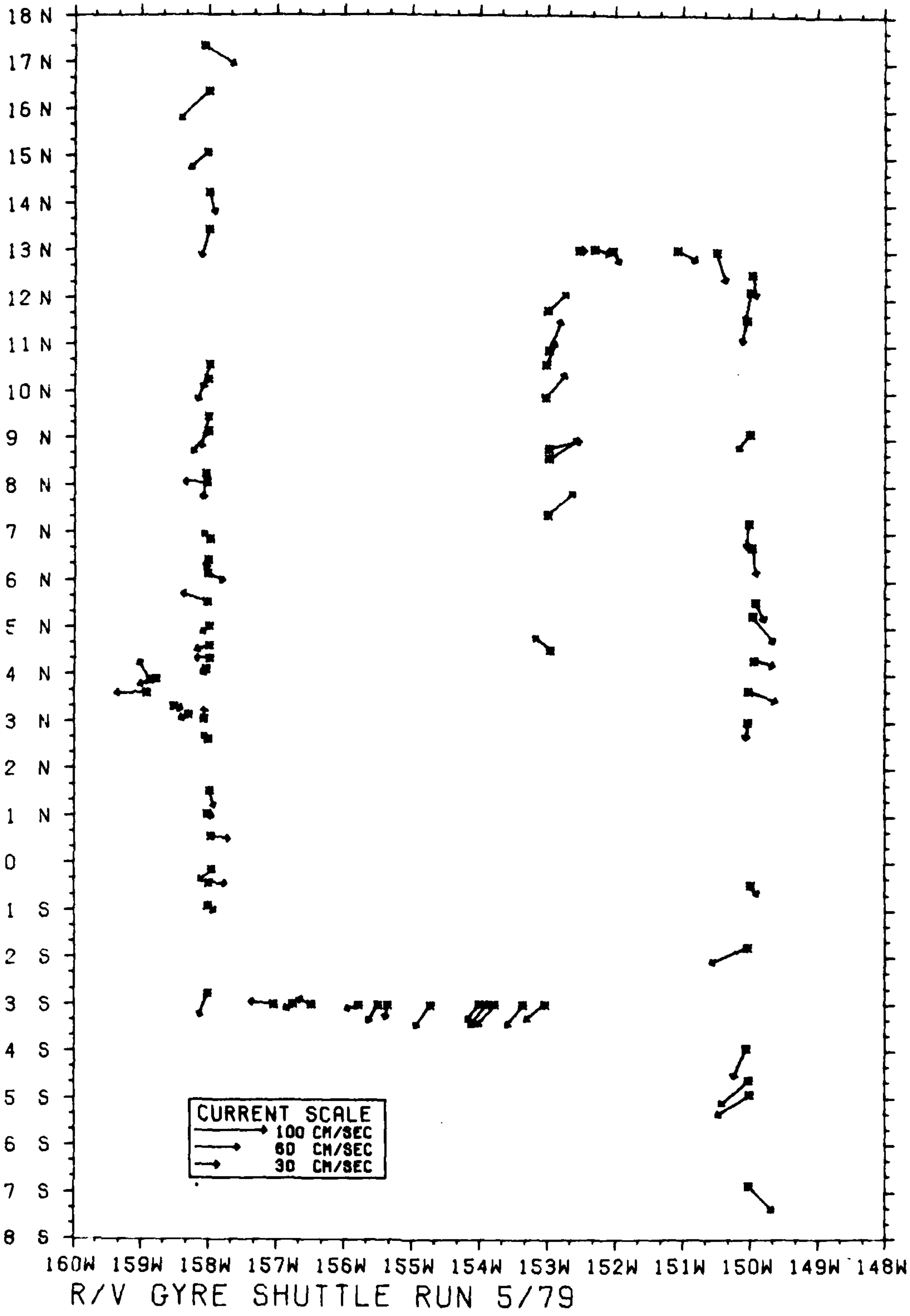


FIGURE 20: R/V GYRE SURFACE CURRENTS

SHIP: R/V GYRE
TIME: SHUTTLE RUN 5/79
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
132:11:54: 0	17	20.90	158	4.10	48	121
132:18:52: 0	16	22.100	157	59.94	56	226
133: 3:42: 0	15	4. 9	158	1.12	32	227
133:10:42: 0	14	13.60	157	59.40	27	166
133:16:42: 0	13	26.57	157	59.89	37	196
134:15:36: 0	10	34.70	157	59.26	33	197
134:17:22: 0	10	16.52	158	0.43	32	208
134:23:12: 0	9	27.40	158	0.20	44	194
135: 1: 4: 0	9	8.20	158	0.40	36	216
135:10:40: 0	8	14.70	158	2.80	33	189
135:11:52: 0	8	2.30	158	1.90	[illegible]	[illegible]
136: 1:10: 0	6	51.70	157	59.80	11	314
136: 3:46: 0	6	25.77	158	1.76	8	197
136: 5:34: 0	6	7.14	158	1.23	22	113
136:13:40: 0	5	32.64	158	1.37	35	288
136:16:54: 0	5	1.95	158	0. 0	[illegible]	229
136:23:23: 0	4	36.88	157	59.21	18	255
137: 1:12: 0	4	20.83	157	59.94	17	271
137: 2:40: 0	4	6.35	158	2.74	7	228
137:12: 0: 0	3	54.20	158	47.60	23	253
137:12:50: 0	3	52.10	158	52.10	29	331
137:22:10: 0	3	37.50	158	54.40	42	270
138: 1:24: 0	3	19.30	158	31.60	8	113
138: 3:15: 0	3	8.33	158	13.35	10	242
138: 5: 2: 0	3	2.45	158	4.54	12	356
138:12: 2: 0	2	37.72	158	1.78	7	316
138:23: 2: 0	1	31.17	157	59.11	21	164
139: 3:54: 0	1	1.35	[illegible]	1.98	5	113
139:11:14: 0	0	33.22	157	58 73	24	97
139:22: 4: 0	0	-10.51	157	57.97	20	231
139:23:42: 0	0	-26.77	157	59.54	22	93
140: 4:32: 0	0	-55.25	158	0.45	9	127
141: 1:32: 0	-2	46.23	158	1.60	32	202
141:13: 8: 0	-3	0.37	157	2.72	32	276
141:14:52: 0	-3	0.30	156	45.10	10	242
141:16:38: 0	-2	59.90	156	29.50	17	293
141:21: 8: 0	-3	1.21	155	47.77	17	253
141:22:56: 0	-3	1.39	155	30.98	24	212
141:23:52: 0	-3	1.65	155	21.22	17	191
142: 4: 2: 0	-3	1.76	154	44.57	35	216
142: 8:46: 0	-2	59.97	154	1.74	24	[illegible]
142: 9:32: 0	-3	0. 5	153	54. 2	36	218
142:10:26: 0	-3	0. 3	153	46.38	36	221
142:13:14: 0	-3	0.23	153	22.85	35	219
142:15:28: 0	-2	59.59	153	2.19	34	233
145:21:12: 0	4	31.40	152	58.41	27	308
147: 0: 8: 0	7	22.35	153	1.72	47	51
147: 9:44: 0	8	34.54	152	59.20	46	56
147:11: 0: 0	8	46. 7	152	59.68	44	75
147:20: 4: 0	9	52.81	153	2.89	41	39
148: 2:38: 0	10	34.17	153	2.11	32	22
148: 4:26: 0	10	52.80	152	59.93	44	23
148:11:58: 0	11	42.42	153	0.23	34	46
149: 0:14: 0	13	0.37	152	33.59	5	88
149: 1:34: 0	13	1.28	152	19.43	18	104
149: 3:18: 0	13	0.30	152	3.73	17	152
149:10: 6: 0	13	1.34	151	6.84	28	116
149:14:36: 0	12	59.89	150	31.79	41	163
149:21:16: 0	12	31.13	149	58.49	29	169
149:23:24: 0	12	9.90	149	59.64	38	191
150: 3:56: 0	11	33.52	150	3. 5	30	194
150:22:38: 0	9	7. 5	150	1.68	26	218
151:15:54: 0	7	13.32	150	2.69	31	185
151:23:36: 0	6	42.60	149	59.55	35	171
152:10:30: 0	5	32.46	149	56.70	26	152
152:12:16: 0	5	15.13	149	58. 0	44	141
152:22: 0: 0	4	19.61	149	57.98	26	103
153: 4: 4: 0	3	41.59	150	2.35	42	110
153: 8: 4: 0	3	0.48	150	2.79	21	189
154:22:10: 0	0	-28.64	149	59.69	14	142
155:12:22: 0	-1	46.12	150	2.39	56	248
156: 7:14: 0	-3	55.17	150	4.62	43	204
156:13:50: 0	-4	37.74	150	1.14	52	231
156:15:38: 0	-4	55.76	150	0.38	54	238
157: 9:54: 0	-6	51.22	150	2.54	47	135

ATLANTIS II (October 14 - November 9, 1979)

In the fall of 1979 the ATLANTIS II made a series of CTD stations in the mid-Atlantic in support of Dr. H. Stommel's Beta Spiral work, and the towed log was deployed during the transits to and from the area. This was an ideal cruise for the instrument since the transits were two long uninterrupted tows through very energetic areas. No major problems were encountered and approximately 300 hours of data were obtained.

During the outward transit the Gulf Stream was crossed and recrossed several times, and fortunately, Loran C coverage was good throughout most of this area so navigation fixes were obtained on a frequent, regular basis. XBT's were dropped every two hours and the currents as measured by the towed log correlated very well with the temperature profiles obtained from the XBT's. The Gulf Stream was crossed obliquely so that its meanders were crossed several times and peak flows of two meters/sec. were observed in several instances. The main flow of the stream persisted to 55°W longitude and several smaller features were noted between there and the termination of the tow at 38°W. There were some problems with the satellite navigator due to heat in the ship's lab which resulted in a few long gaps in the data after the Loran C coverage was lost, but after this was overcome the fixes were fairly regular and seemed to be of generally high quality.

Following the station work, the log was towed from 26°N to 38°W straight south with stops for CTD stations every 24 hours. The tow was then terminated at 2°N. During this period there appeared to be an unexplained bias in the heading of two to three degrees which was taken into account during the processing. The resulting currents show slight eastward flow (20 to 40 cm/sec.) around 21°N and then a strong current (150 cm/sec.) between 10°N and 3°N.

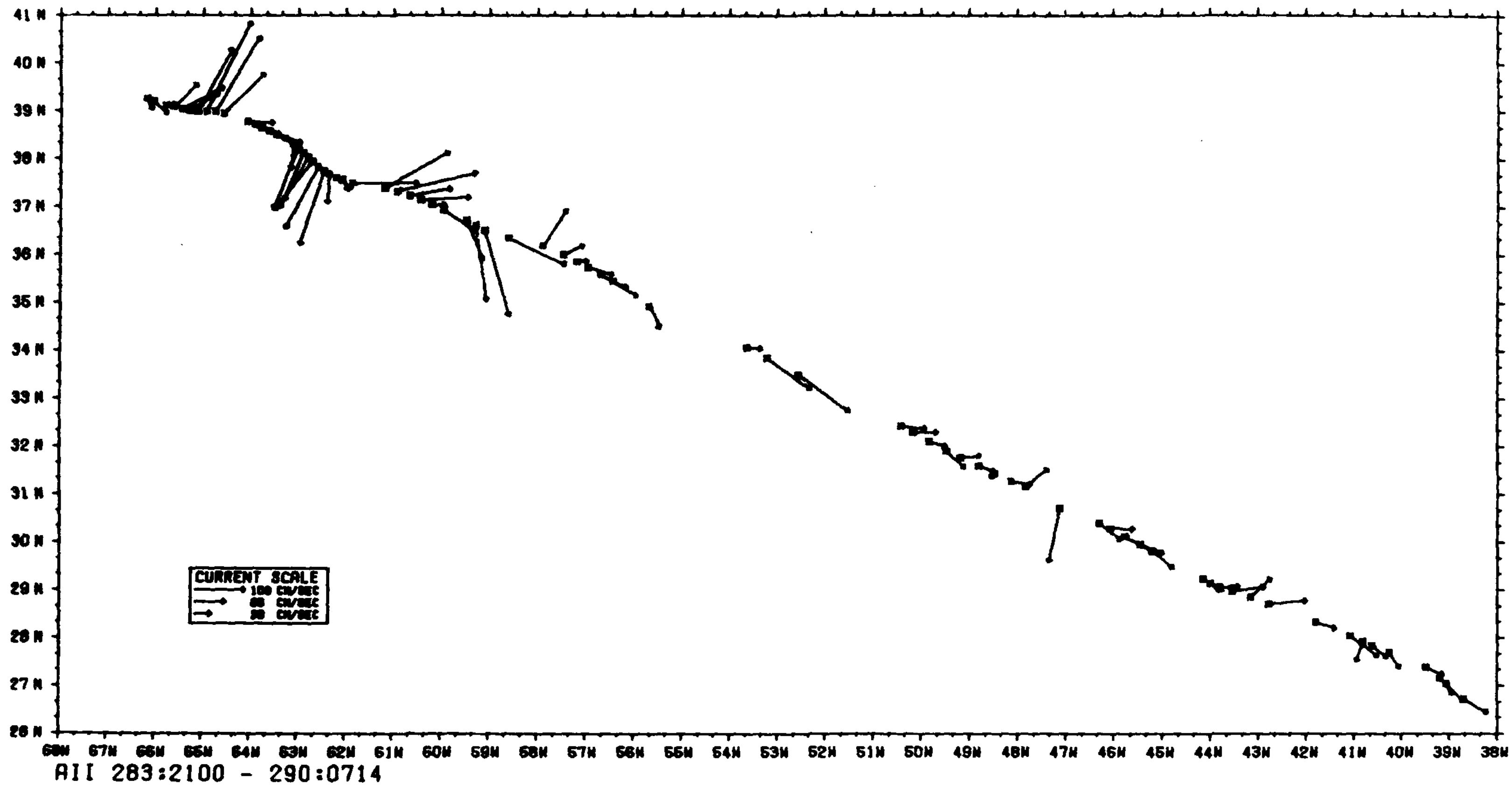


FIGURE 21: ATLANTIS II 1979 SURFACE CURRENTS

SHIP: ATLANTIS II
TIME: 283:2100 - 290:0714 1979
NAVIGATION: SATELLITE & LORAN C

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
283:21: 0: 0	39	15.50	66	12.85	23	154
283:22: 0: 0	39	12.100	66	3.70	34	133
284: 0: 0: 0	39	7. 5	65	47. 6	15	84
284: 1: 0: 0	39	5.80	65	37.40	64	46
284: 2: 0: 0	39	2.100	65	27.68	92	62
284: 3: 0: 0	38	60.97	65	17.45	64	58
284: 4: 0: 0	38	59.20	65	7.40	145	29
284: 5: 0: 0	38	59.20	64	56.40	205	27
284: 6: 0: 0	38	59.70	64	45.40	179	31
284: 7: 0: 0	38	57.80	64	35.80	114	46
284:10: 0: 0	38	46.30	64	5.70	50	93
284:11: 0: 0	38	43.50	63	55.10	53	114
284:12: 0: 0	38	39.85	63	47.16	56	114
284:13: 0: 0	38	34.25	63	38.62	65	117
284:14: 0: 0	38	30.86	63	28.18	50	108
284:17: 0: 0	38	18.90	63	7.90	48	185
284:18: 0: 0	38	13.60	63	1.20	131	202
284:19: 0: 0	38	7.90	62	54.20	101	202
284:20: 0: 0	38	1.30	62	48.80	116	210
284:21: 0: 0	37	56.81	62	43.65	125	219
284:22: 0: 0	37	49.50	62	36.80	141	208
284:23: 0: 0	37	44.10	62	28.30	157	198
285: 0: 0: 0	37	40.19	62	22.84	56	183
285: 1:10: 0	37	36.71	62	12.18	34	126
285: 2: 0: 0	37	33.22	62	5.23	21	153
285: 3:12: 0	37	29.29	61	52.93	131	90
285: 6:42: 0	37	22. 2	61	12. 2	150	61
285: 8: 2: 0	37	18.97	60	56.62	165	77
285: 9:32: 0	37	13.92	60	40.33	84	80
285:10:48: 0	37	8.61	60	27.83	98	87
285:12:30: 0	37	1.45	60	13. 7	24	93
285:14: 0: 0	36	55.72	59	58.81	73	124
285:17: 0: 0	36	42.100	59	29.80	84	158
285:18: 0: 0	36	36.50	59	18.80	155	172
285:19: 0: 0	36	29.10	59	7.70	181	164
285:21:30: 0	36	20.76	58	36.19	125	116
286: 1:24: 0	36	10.12	57	54.99	85	34
286: 4: 4: 0	35	59.71	57	28.32	42	65
286: 5:52: 0	35	50.93	57	12.10	19	84
286: 7:18: 0	35	43.75	56	58.12	50	107
286: 9: 0: 0	35	34.72	56	42.54	56	117
286:10:32: 0	35	25. 3	56	27.95	54	121
286:16: 0: 0	34	54.98	55	41.16	45	154
287: 4:58: 0	34	2.10	53	39.40	27	92
287: 6:48: 0	33	49.50	53	14.20	107	126
287: 9:42: 0	33	28.45	52	35.12	126	126
287:20:10: 0	32	24.45	50	26.48	47	96
287:21:24: 0	32	17.67	50	12.66	46	89
287:23: 8: 0	32	6.50	49	51.45	32	107
288: 0:56: 0	31	53.11	49	30.27	46	132
288: 2:22: 0	31	45.92	49	13.61	38	84
288: 4: 8: 0	31	35. 3	48	51.58	31	108
288: 5:56: 0	31	25.10	48	30.56	7	229
288: 7:28: 0	31	16.35	48	10.35	37	101
288: 8:52: 0	31	9.23	47	53.67	56	53
288:12:44: 0	30	42. 9	47	9.49	109	192
288:16:22: 0	30	24.81	46	20.39	53	129
288:17:30: 0	30	17.80	46	7.54	46	91
288:19: 0: 0	30	7.95	45	48.21	63	118
288:20:48: 0	29	57.58	45	29.83	46	111
288:22: 2: 0	29	48. 7	45	14. 8	52	129
289: 3:16: 0	29	14.98	44	11. 0	44	121
289: 4:10: 0	29	8.93	44	2.69	20	126
289: 5: 6: 0	29	3.31	43	50.74	36	88
289: 6:16: 0	28	58.71	43	34.10	64	82
289: 8: 4: 0	28	50.25	43	11.15	54	47
289: 9:46: 0	28	42.90	42	48.37	75	85
289:15: 8: 0	28	19.15	41	49.82	40	108
289:18:30: 0	28	2.71	41	6.58	69	126
289:19:58: 0	27	54.42	40	50.57	38	198
289:20:56: 0	27	50.57	40	38.66	36	128
289:22:44: 0	27	41.56	40	16.86	32	146
290: 2:26: 0	27	23.50	39	30.18	36	114
290: 4:12: 0	27	9.27	39	12.95	38	141
290: 5: 0: 0	27	2.28	39	4. 3	49	136
290: 7:14: 0	26	43.13	38	42.64	52	121

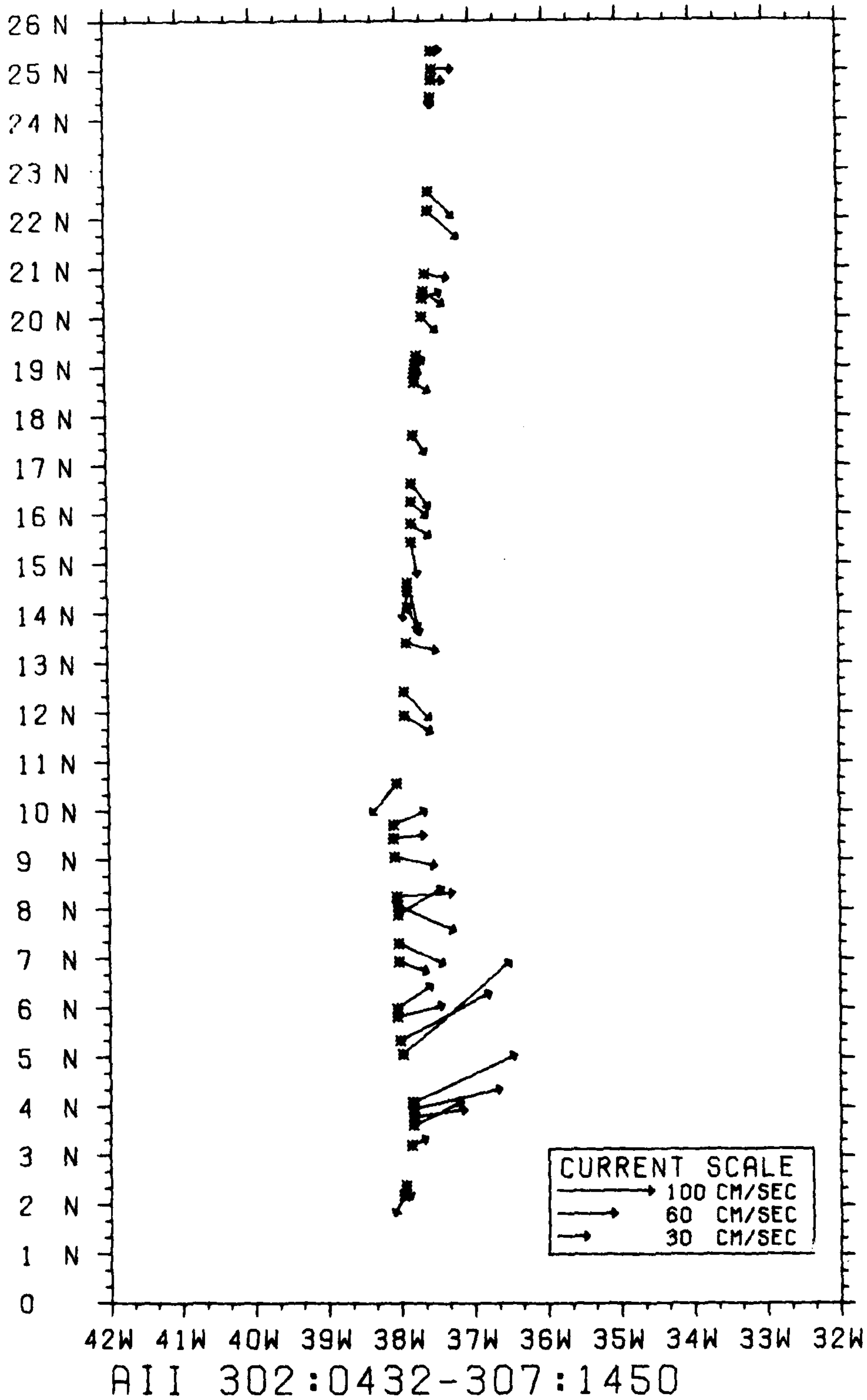


FIGURE 22: ATLANTIS II 1979 SURFACE CURRENTS

SHIP: ATLANTIS II 1979
TIME: 302:0432 - 307:1450
NAVIGATION: SATELLITE

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
302: 4:32: 0	25	23.26	37	30.64	6	86
302: 6:22: 0	25	1.100	37	30.51	19	89
302: 7:30: 0	24	47.29	37	30.88	10	95
302: 9:12: 0	24	26.36	37	31.52	7	185
302:20:24: 0	22	31.15	37	34.10	35	135
302:22:10: 0	22	8.50	37	34.80	40	133
303: 5:40: 0	20	51.87	37	36.29	23	99
303: 7:22: 0	20	30.78	37	37.41	22	124
303: 8: 6: 0	20	21.81	37	38.93	17	69
303: 9:50: 0	19	59.21	37	39. 4	19	135
303:16:42: 0	18	50.83	37	45.99	3	92
303:17:40: 0	18	39.92	37	45.30	15	121
303:22:52: 0	17	34.72	37	47.74	20	146
304: 4:46: 0	16	35.83	37	48.35	28	145
304: 6:34: 0	16	13.57	37	48.49	19	133
304: 8:40: 0	15	46.27	37	48.41	21	123
304:10:28: 0	15	23.32	37	49.64	32	169
304:15:46: 0	14	35.83	37	51.45	53	167
304:16:34: 0	14	25.89	37	52. 2	28	191
304:18:18: 0	14	4.40	37	53.71	22	149
304:21:44: 0	13	22.16	37	53.29	31	103
305: 3:30: 0	12	23.79	37	56.80	37	135
305: 5:48: 0	11	54.72	37	56.79	31	118
305:13:38: 0	10	32.28	38	1.48	40	221
305:19:18: 0	9	41.20	38	4.23	35	64
305:20:38: 0	9	25.80	38	4.42	31	83
305:22:24: 0	9	3.95	38	4.67	42	102
306: 3:28: 0	8	15.74	38	2.88	58	86
306: 4:20: 0	8	4.99	38	2.55	64	114
306: 5:18: 0	7	53.60	38	1.21	53	58
306: 8:10: 0	7	18.52	38	0.44	49	114
306: 9:54: 0	6	56.84	38	1.62	29	109
306:15:46: 0	5	59.16	38	2.43	42	55
306:16:40: 0	5	49.72	38	2.48	48	75
306:19:34: 0	5	19.41	37	60.72	107	61
306:21:16: 0	5	3.48	37	58.86	151	49
307: 3:22: 0	4	6.58	37	50.38	120	66
307: 4:14: 0	3	57. 0	37	50.59	94	77
307: 5:10: 0	3	48.68	37	49.44	53	82
307: 6:16: 0	3	37.23	37	49.34	55	64
307: 8:46: 0	3	12.26	37	51.92	15	62
307:13:38: 0	2	24.74	37	56.16	10	159
307:14:50: 0	2	12.72	37	58.81	19	206

OCEANUS (December 7 - December 10, 1979)

As part of Dr. Val Worthington's study of Gulf Stream transport in the North Atlantic the towed log was deployed from R/V OCEANUS in December 1979 and used to help locate the Gulf Stream. Unfortunately, time did not permit rigging the tow from the starboard side of the ship to keep it away from the XBT's, and the deployment had to be terminated prematurely to prevent the XBT wire from being cut by the tow cable.

However, while it was deployed, the sea surface temperature and the real time current display proved extremely useful in defining the boundaries of the stream.

SHIP: R/V OCEANUS
TIME: DECEMBER 6-7,1979
NAVIGATION: LORAN C

TIME	TRUE POSITION				SPEED (CM/S)	DIR. (DEG)
340:21:11: 0	40	37.37	70	28.40	58	113
340:22: 0: 0	40	28.30	70	22.10	57	113
340:23: 5: 0	40	16.31	70	14.33	49	134
341: 0:12: 0	40	4.26	70	6.89	33	108
341: 1: 5: 0	39	55.22	69	58.41	72	70
341: 2: 0: 0	39	46.70	69	51.10	60	79
341: 3:15: 0	39	32.50	69	41.64	122	80
341: 4: 0: 0	39	25.64	69	34.29	137	74
341: 5: 0: 0	39	14.72	69	25.28	136	86
341: 6: 0: 0	39	3.73	69	17.56	127	88
341: 7: 0: 0	38	51.49	69	8.52	166	89
341: 8: 0: 0	38	40.13	68	60.86	119	95
341: 9: 0: 0	38	28.60	68	59.90	123	141
341:10: 0: 0	38	16.80	68	59.80	107	143
341:11: 0: 0	38	4.20	68	58.100	124	125
341:14: 4: 0	38	2.60	69	3.50	179	105
341:15: 0: 0	38	8.90	69	9.60	98	103
341:16: 0: 0	38	15. 0	69	16.70	72	91

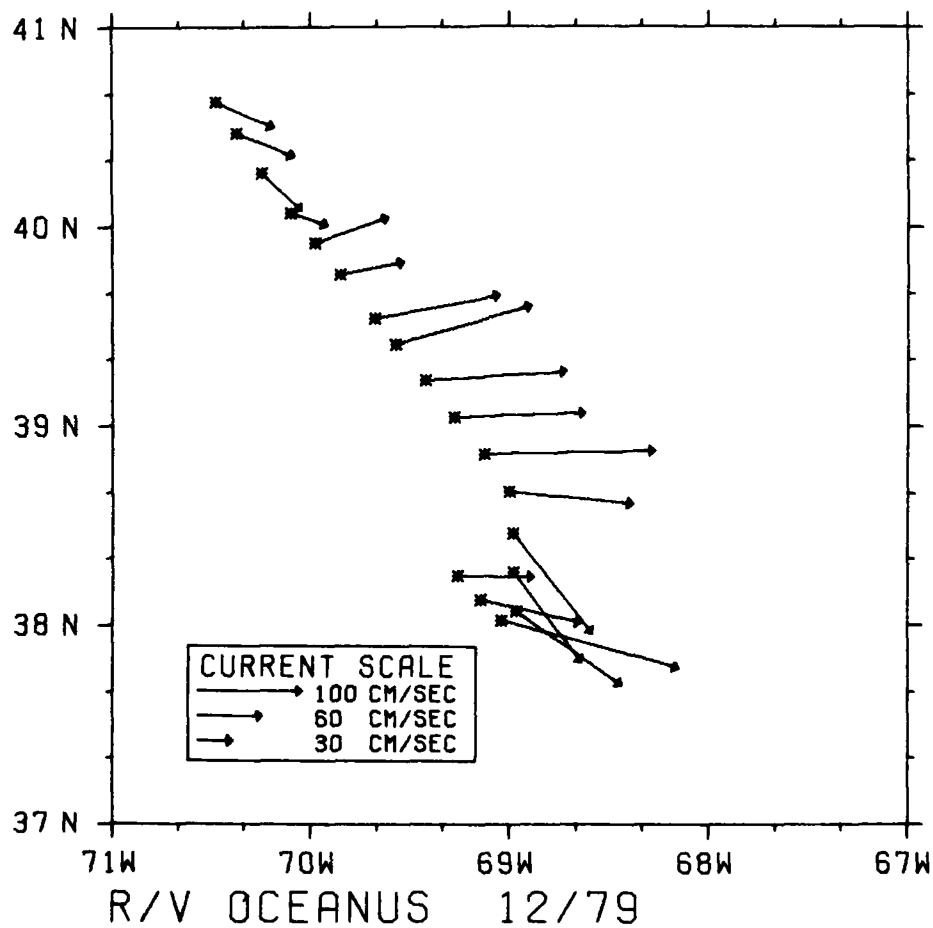


FIGURE 23: R/V OCEANUS SURFACE CURRENTS

THOMAS WASHINGTON (January 14 - February 15, 1980)

As part of the Pacific Fronts experiment the towed log was to be used to map surface currents during the transits to and from the operating area north of the Hawaiian Islands. Unfortunately, after towing for two days during the outbound transit from San Diego, the speed sensor was knocked off during a rough weather deployment following a CTD station. The electronics case flooded and despite heroic efforts by the operator, the bearings and slip rings in the gyro compass gimbal assembly were damaged beyond repair.

CONCLUSIONS

This project has demonstrated the feasibility of using a ship towed log for measuring ocean surface currents. Most of the original goals have been realized in that the system is reasonably portable, and requires a minimum of operator effort to deploy and operate. Although the fish does not tow exactly as predicted in the design equations, its performance was entirely satisfactory as a platform for the sensors. All the components have proven to be very reliable and all losses of data have been due to operator error or damage to the system. As designed, the system is well suited to research ship-of-opportunity work, but could probably not be deployed and recovered from large merchant ships without damage.

It is difficult to define the overall system level accuracy. The speed sensor has performed well and is probably within 1% of the true speed. Based on the test results with the navigation sets, an RMS position error of 200 meters seems reasonable, if not conservative. The error bounds of the heading sensor present the most difficulty. The data from the SHACKLETON and the first ATLANTIS II deployments were very consistent and reasonable when analyzed, whereas the data from the GYRE and the second half of the second ATLANTIS II deployment had obvious biases in the heading data. On both of the latter cruises the fish was towed from the side of the ship, and although it was well aft, the fish may have been affected by the ship's wake. This should be investigated in any future deployments.

In addition to the performance of the sensor itself, there is the question of the magnetic-to-true north corrections and the model of the earth used in the current calculations. Comparisons of the magnetic-to-true north corrections from various sources have shown discrepancies of up to one degree and it is not known how much the local distortions of the field differ from the published values. The model of the earth was derived from the World Geodetic System (WGS) of 1972 which is the model used by the TRANSIT satellite navigation system for calculating navigational fixes. However, on occasion there have been apparent inconsistencies in converting distance run to geographical coordinates.

Based on the results of all the field tests, the towed log appears to be able to distinguish features on the order of 20 to 30 cm/sec, although it may be better than this because the data contains all the high frequency components of the small scale circulation of the surface water. While this system will never provide high precision data such as is obtained from moored current meters, it does provide the capability of mapping the currents over a large horizontal scale in a part of the ocean that has been very difficult to instrument in the past using traditional moored current meter techniques.

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A ship towed log for use on ships-of-opportunity to measure ocean surface currents was built and tested over the past two years. The technique used is one of the oldest known to navigators. This ship's dead reckoned position is calculated from the speed and heading as measured by the towed log. This is then compared to the ship's true position as obtained from a reference navigation system (Loran, satellites, etc.) and the difference is attributed to the currents encountered by the ship. The system was used on six sea cruises and was successfully towed over 11,000 miles. While it is not capable of making high precision current measurements as would be obtained from moored current meters, it can distinguish features on the order of 20 to 30 cm/sec. over a large horizontal scale in the upper ocean.

1. Currents
2. Current Meters
3. Towed Body

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